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Waking Effectiveness of Household Smoke and Fire Detection Device

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Notice

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WAKING EFFECTIVENESS OF HOUSEHOLD SMOKE AND FIRE DETECTION DEVICES

E. Harris Nober, Henry Peirce, Arnold Well,
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Abstract

Experiment A assessed intensity-frequency characteristics of several smoke alarm signals. Overall dBA levels of detector acoustic signals were obtained at 10 feet from the source in an anechoic chamber and reverberant chamber. Smoke alarm signals were analyzed at nine octave bands and with refined analyses of 1/3 octave bands.

At 10 feet the alarm output mean was 85 dBA with a range from 80 to 92 dBA. In the anechoic chamber octave band energy peaks generally occurred at 4000 Hz with a second energy cluster at 2000-3000 Hz. Reverberant room energy peaks occurred at 4000-5000 Hz. Directional axes variations in energy were up to 10 dBA in the anechoic chamber and 3.5 dBA in the reverberant room.

Experiment B quantified sleep-waking behavioral performance relative to the alarm signals and extraneous environmental noise background. This component employed 70 college-aged subjects (18-29 years) who received electronically controlled sound stimuli. The major dependent variable was the time taken to respond to the onset of the alarm signal. Experiment B included variables such as alarm sound level (85, 70, 55 dBA), presence of 63 dBA air-conditioner background noise, hours into sleep, night of the week, sex, VCR/TV. SPL was equated to alarm levels calculated earlier from 10 feet (85 dBA), at pillow site, bedroom door open (70 dBA) and bedroom door closed (55 dBA). Sound level was controlled using a tape recorded alarm signal of the current electromechanical horn used in most household dwelling detectors. One dwelling member served as respondent and performed two tasks when awakened by the alarm: (1) deactivated the automated apparatus, and (2) phoned the local fire department. The subject also filled out a pre-alarm and post-alarm questionnaire for pertinent behavioral and supplemental data. Response latency and behavioral data from the two questionnaires provided an index of expected behavior to current alarms in households by profiling stress-reaction patterns of individuals and families when suddenly awakened from nighttime sleep in different living conditions, day(s) of the week,

alarm levels, alarm modes, alarm installation sites, environmental noise waking conditions, age, etc.

Data for the 30 Ss who received the alarm signals at 55, 70 or 85 dBA (10 Ss each signal level) showed mean response latencies (alarm-on to alarm turned off by Ss) of 14, 10, and 7 seconds respectively for the three levels. T-tests revealed significant differences between 55 dBA and 70 dBA, 55 dBA and 85 dBA, but not between 70 dBA and 85 dBA. Other data also included time required to phone the fire department.

Data for the 20 Ss who received the 55 dBA alarm (10 Ss) and the 70 dBA alarm (10 Ss) with a taped air-conditioner background noise (63 dBA measured 12 inches from source, but 51 dBA mean at pillow position) showed a mean response latency of 43 seconds for 55 dBA alarm and 19 seconds for the 70 dBA level. T-tests revealed significant waking time differences.

Twenty subjects received alarm levels of 55 dBA (10 Ss) and 70 dBA (10 Ss) while viewing a video-taped recording in the privacy of their own bedroom. These subjects were awake when the alarm signal was activated as compared to all other data obtained after subjects were awakened from sleep. The video sound volume was set at "comfortable level" by each subject. Thus, the video volume range extended from 40 dBA to 68 dBA. Mean response latency was 10 seconds at 55 dBA alarm level and 6 seconds at 70 dBA level. T-tests revealed that this difference was significant.

A series of t-tests were performed comparing the alarm levels relative to the three listening condition variables, i.e., quiet, air-conditioner noise, video-taped TV movie. Generally, it took significantly longer time to be awakened and respond with the air conditioner background noise occurring although the absolute values amounted to 30 seconds or less. The shortest response latencies were with the VCR/TV mode; it is noteworthy that VCR/TV subjects were not asleep in the VCR/TV experimental condition.

Pre- and post-alarm trial questionnaire data on subjects' attitudes were collated and analyzed.

Conclusion: College-aged subjects can be awakened and alerted by smoke detector alarm levels as low as 55 dBA even with extraneous background noise when sufficiently sensitized to the signal and motivated to respond accordingly.

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WAKING EFFECTIVENESS OF HOUSEHOLD SMOKE AND FIRE DETECTION DEVICES

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1. OVERVIEW OF THE PROGRAM RELATIVE TO CFR DIRECTIONS

Public concern about fire safety has led to a notable national effort that costs about $10 billion annually (NBS/CFR Report 1980). A hallmark step toward improving fire safety occurred in 1974 when Congress established the Center for Fire Research (CFR) as part of the Federal Fire Prevention and Control Act. The Center was intended to provide research on the physics and chemistry of fire, its behavior in buildings and elsewhere, and a means of mitigating these effects on people.

This same law also established the National Fire Prevention and Control Administration (now called U.S. Fire Administration) to "train and educate fire professionals, to increase public awareness of fire and its hazards and protect the health and safety of firefighters." The significance for the safety of firefighters is not always clear to the general public as most people are unaware that half of the 8,700 annual U.S. fire deaths involve firefighters who succumb to smoke and hot gasses. Of this 8,700 total, 72% of the deaths occur in residential home fires where furnishings become ignited accidentally. Smoking alone causes 27% of the residential home fires. Actually, any "scenarios involving more than 2% of the fire deaths occur in the home" (CFR Report 1980). In addition to fire deaths there are 84,000 fire injuries reported each year, half of which again involve firefighters. Property loss in 1977 was approximately $4.4 billion with about half divided between residential fire loss and other structures. In order to reduce the detrimental effects of fire, a national goal has been established to reduce losses and injuries from fire in half by 1995.

One of the most cost effective household design innovations to reduce injury has been the widespread promotion of household smoke detectors. This important advance became a main thrust of the U.S. Fire Administration (USFA). Complementing the efforts of the USFA is the Center for Fire Research (CFR), which is geared to synthesize fire science research, and to establish procedures for accurate measurement and prediction of fire risk by investigating specific materials, designs, products and fire-related practices. One segment of these activities includes studying human needs and behavior during fire stress scenarios.

The goals and objectives of this project, "The Waking Effectiveness of Household Smoke Detection Devices," are consistent with the objectives established by the CFR. This three-year program involves three major goals, each with its own specific objectives (Figure 1, Time-Flow Chart). An expectancy profile of human behavior during fire alert stress should provide basic information which will be useful in meeting the goals of the national fire safety program. Since most fire deaths occur in home residences during sleeping hours (as opposed to other fires that occur during working/waking hours), this investigation explored the sleep arousal effectiveness of home smoke detector alarm signals with young adults under a variety of household acoustic conditions, and their patterns of behavior and subject task performance under different conditions.

The project purports to answer the following questions: (1) How effectively do smoke detector alarms awaken people? (2) What is the expected pattern of behavioral performance when people are suddenly awakened from sleep? (3) What improvements can be made to enhance safety? The questions were delineated into three major goals for the three-year project:

1.1 Goal I

Goal I was to assess the intensity-frequency spectral characteristics of several smoke alert detector signals; this component was designated Experiment A. Overall dBA levels of detector acoustic signals were obtained at 10 feet from the source in an anechoic chamber and at other locations simulating typical household placement sites. Smoke alarm signals were analyzed at nine octave bands with central frequencies 63, 125, 250, 1000, 2000, 4000, 8000, 16000 Hz; refined analyses included 1/3 octave bands. Tests compared data elicited in an anechoic chamber and in a reverberant room.

1.2 Goal II

Goal II quantified and profiled sleep arousal behavior performance to a smoke detector alarm signal using different noise background conditions. Four experiments were designed to provide the data for

Figure 1

Time-Flow Chart
Goals-Objectives-Experiments

Goals	Objectives	Experiments
Goal 1 Assess Spectral Characteristics of Alarm Signals	**Objective 1** Sound Levels at Various Placements	**Year 1** **Experiment A** Tested 5 Smoke Alarm Units 5 months
	Objective 2 Intensity/Frequency Spectral Composition	
Goal 2 Sleep-Waking Responses to Alarm Signal	**Objective 1** Waking Responses 55, 70, 85 dBA, taped signal in quiet (Experiment B). Bacn adds AC noise. Bvcr adds TV movie.	**Experiment B** 30 Ss **Experiment Bacn** 20 Ss **Experiment Bvcr** 20 Ss 7 months
	Objective 2 Validate Response Protocol and Questionnaire	
	Objective 3 Field Test Actual Alarm Units in Homes	**Year 2** **Experiment C** 80 Ss 12 months
Goal 3 Explore New Innovative Alarm Signals	**Objective 1** New Signal Temporal Patterns	**Year 3** **Experiment D** 12 months
	Objective 2 New Signal Intensity/Frequency	
	Objective 3 New Signal re: Ss Psychoacoustics	

Goal II. During the first year, Experiments B, Bacn, and Bvcr/TV tested 70 college-aged subjects who received experimentally controlled detector alarm stimuli. Experiment B used three alarm levels (55, 70, 85 dBA), and tested for sex differences, hours into sleep, night of week, etc. The three sound levels equated to alarm means determined in a pilot study from a ten-foot distance (85 dBA), at pillow site, bedroom door open (70 dBA) and at pillow site, bedroom door closed (55 dBA). Sound level was controlled by using a tape recorded smoke detector alarm signal (Kobishi-type electromechanical horn). One household member served as respondent and performed two behavioral tasks when (or if) awakened by the alarm: (1) deactivating the automated apparatus and (2) phoning the Amherst Fire Department. Both responses were recorded and the times necessary to perform the responses ("shut-off latency" and "phone-call latency") were obtained. The same person also filled out a pre-alarm and a post-alarm questionnaire that contained pertinent behavioral and other supplemental environmental data.

Experiment Bacn was essentially the same as Experiment B in design and protocol except that a 63 dBA air-conditioner noise (acn) was generated throughout the evening via a loudspeaker placed at a window location.

Experiment Bvcr/TV used a video taped movie but differed from the other two components of Experiment B as the subjects were awake watching TV when the alarm signal was electronically activated. Thus, all three Experiment B components, used electronically controlled signals on young normal hearing adults—highly motivated and sensitized to the task. These subjects provided the optimal baseline data to determine a smoke alarm stress-related performance profile for future reference.

Experiment C, planned for the second year, is the first of these "future investigations." It is the actual "live" field-based study of smoke detector units installed in home dwellings to sample evacuation behavior in households with and without children, distributed as a function of households of subject age, apartments vs. one family homes, and time of year (winter vs. summer). Detectors will be activated by a remote RF signal no sooner than four weeks after installation—to insure a densensitization period to the visual presence of the detector units. Two detector units will be installed, one unit fully capable of normal operation and a second experimental unit under the remote control of the experimenter (using an RF signal transmitter). Subject response requires occupants to turn on a light when awakened and then for all household occupants to evacuate the premises to street side of the front door. Nearby, the experimenter and a fireman will be waiting in a car with stop watches to time and record the entire waking-evacuation scenario.

1.3. Goal III

Goal III will explore new and efficacious acoustic auditory stimuli for different household sleeping conditions and different population types such as the handicapped and aged. Future tests will examine different signal temporal patterns for sleep arousal (Experiment D). Additional signal variations will include a speech signal, a combination of speech and tone, etc. These plans are projected as a third year component.

1.4. Focus of First Year Investigation

The current first year of the UMass project investigated the acoustic signals of commercial smoke detectors (Experiment A), subject response latency to a detector alarm signal, and task performances using college-aged young adults as subjects (Experiments B, Bacn, Bvcr). The three dBA alarm levels used in Experiment B, (55, 70, 85 dBA) were determined in a pilot study by Nober. Accordingly, the 85 dBA experimental level corresponds to manufacturer specifications concerning average output within a 10-foot radius; the 70 dBA experimental level represents the average obtained at ear/pillow position in bedrooms with the bedroom doors open and the detector installed in a hallway; 55 dBA represents the ear/pillow level with the bedroom door closed. These three values are also consistent with the three levels outlined by Berry (1978) as well as the NFPA (1974) Standard for Household Warning Equipment. For example, NFPA (1974) found 15 dB attenuation when the sound had to penetrate bedroom doors, and Bradley and Wheeler (1977) found a 16.4 dB attenuation.

Other criteria and variables for the overall experimental design of the study were based on data reported in the research literature. The results obtained in Experiments A, B, Bacn and Bvcr and the pre- and post-questionnaires will be compared to other pertinent studies. Hence, a brief updated review of the literature is presented for reader convenience since the detailed literature review of the original grant proposal (May 1978) coupled with some original Nober pilot research formed the foundation of the experimental rationale and design.

2. LITERATURE REVIEW UPDATE

2.1 Sleep and Sleep Stages

Sleep is a complex multiphasic process that can be delineated into stages. Research data results elicited during sleep are related to response measures, stimulus type and method of presentation, age, sex, time-of-night, signal significance, motivation and attitude, physical and mental condition, etc. While most of the sleep studies are conducted in the "sleep laboratory," several were carried out in homes and more natural environments. Lukas (1973) reported correlations between results obtained in the home and laboratory environments, and Penzolt and Van Cott (1978) stressed the "best setting for such experimentation would be in the subject's residence." As indicated earlier, all three components of Experiment B in this project were conducted in the home setting.

Data from sleep laboratory studies show the least amount of stimulus intensity is needed for arousal during sleep stage 1 while greater stimulus intensity is needed for stages 3 and 4 (Delta) which comprise the first half of sleep. Delta is often designated as "deep sleep."

During REM (rapid-eye-movement) sleep the arousal stimulus intensity is similar in magnitude to stage. REM which is identified with dreaming and the latter half of the sleep cycle (Webb, 1969), appears about 90 minutes into sleep and reappears cyclically every 90-100 minutes. Although sleep stage is predictably sequential, there is considerable individual variability and group dispersion. Individuals appear programmed according to age and sex; nevertheless, individuals will spend their own amounts of time in the different stages. Daves (1976) studied young adults and found 5% of the total sleep was spent in stage 0 and stage 1, 50% in stage 2, 20% in stages 3 and 4, and 25% in REM. Lukas (1973) pointed out that stage 4 becomes shorter and decreases with age and that this change is more pronounced in men than in women. While arousal threshold for auditory stimuli is a function of sleep stage, stage is not used as a variable in home field studies. Hopefully, in this current UMass project, the effect of sleep stage was "averaged out" or minimized by randomizing the time of alarm presentation across subjects.

2.2 Stimulus Parameter

In sleep research, as in other types of experimental exploration, the stimulus and response parameters markedly determine the nature of the elicited data and subsequently the final analyses. Generally, in sleep research, the stimulus for auditory arousal has been a pure tone, usually of 1000 Hz, with designations for repetitions and method of presentations, duration, rise-time, impulse vs. steady state ascending/ descending presentations, etc. Most of these variables have been studied with related threshold differences (research by Steinicke, reported by Lukas, 1973). The alarm stimulus used in this current study was a complex sound that had peak energy between 2000-4000 Hz.

2.3 Response Parameter

Sleep response data conducted in the sleep laboratory can include EEG changes, sleep stages shifts, EEG arousal, physiological changes (respiratory, cardiac, autonomic), behavioral response such as frequency of awakening, taping microswitch pushbuttons, vocalizations, phone calls, stimulus counting (Ludlow and Morgan, 1972). Performance following arousal from sleep was highly variable and markedly inferior to performance when fully awake, i.e., 15-360 percent (Tebbs, 1972); performance also varies depending on the sleep stage in which awakening occurred. Johnson (1973) reported the more effective performance responses occurred from awakenings in stage 2 and REM.

2.4 Magnitude of Stimulus

In most instances, increases and decreases of stimulus intensity imposes corresponding changes on the responses. Thus, an increase of stimulus intensity precipitates increases in the number of behavioral arousals and EEG changes. Data on auditory arousal thresholds report a wide range, depending on the variables. Pooling all the variables, arousal thresholds have been reported from tones 48 to 79 dB (Bradley and Meddis, 1974). Zimmerman (1970), in a study of "deep and light" sleepers, reported a tone range from 31 to 85 dB with a median of 65 dB. Bonnet, Johnson and Webb (1978) studied "good" and "poor" sleepers for auditory arousal from a 1000 Hz tone. This study had two experimental components — a San Diego component and a Florida component. The San Diego study reported a mean arousal threshold of 74.5 dB for the good sleepers and 78.0 dB for the poor sleepers; the difference was not statistically significant. The range was 67.1 dB (morning REM/stage 2) to 91.6 dB (stage 4). The Florida component did not substantiate the San Diego data and reported a tone range of 45.3 (stage 2) to 51.8 dB for auditory arousal. In a study dealing with the effects of drugs on auditory arousal from sleep, Bonnet, et al. (1979) reported a placebo threshold of 43.2 dB, pentobarbital, 51.7 dB and flurazepam 47.2 dB. Shapiro et al. (1963), using a bell as the stimulus and lifting the telephone receiver as the response, reported a mean tone arousal threshold of 55 dB. Several researchers reported arousal thresholds to a stimulus around 75 dB (Keefe, Johnson and Hunter, 1971; Berry, 1978; Johnson et al., 1979).

In the Johnson et al. (1979) study, arousal threshold means (to a 1000 Hz tone) were 76 dB ± 19 dB for "self-proclaimed good sleepers" and 79 dB ± 15 dB for "self-proclaimed poor sleepers." The "good sleeper" (Johnson et al., 1979) 40 dB difference exceeded the Bradley and Meddis (1974) range. Terms like good and poor, deep and light are often equated in the sleep literature. Monroe (1979) reported self-proclaimed good sleepers spent more total time asleep, had more REM and less stage 2. Poor sleepers took longer to reach delta and REM.

2.5 Other Variables

A host of variables can affect the sleep and waking cycles. For example, the nature of the experimental instructions to the subject can impose substantial alterations in responses during sleep, throughout all sleep stages. It is also possible for subjects to awaken themselves at predetermined or self-determined times. Tart (1970) found statistically significant responses related to preselected hours in both the laboratory and home environments. He differentiated two kinds of "self-awakening" responses, (1) the subject awakened once during night "on target" hour and (2) the subjects awakened several times approximating the target hours until they zeroed in exactly. In this current UMass project subjects were told the alarm would become activated within a 7-day period between the hours of 12:00 p.m. and 6:00 a.m.

A first-night-effect has also been reported by Agnew et al. (1966); they noted EEG responses in laboratory sleep contained more awake periods and less stage 1-Rem and more stage 0 but all changes adapted by the second night of sleep. Agnew et al. (1966) recommended eliminating the first night from the baseline data. In this UMass study, the first night was never used as the target night.

Time-of-night has been cited as a variable affecting response although there is not always agreement among experimenters. For example, Zimmerman (1970) found responsiveness increased as a function of time into night but Williams et al. (1964) observed a decrease as a function of time into night (hours of sleep). Williams (1973) noted auditory arousal thresholds decreased as sleep time increased. In this current project, time of the night was experimentally programmed.

Age clearly affects sleep and response from sleep. It would be presumptious to predict sleep response behavior of a geriatric population from data collected on college-aged subjects. Older subjects awaken faster, have less stage 3 and stage 4, have increased latency to sleep onset and increased spontaneous awakening — hence, greater frequency of arousal with advancing age. The elderly have shorter "grogginess" periods after arousal, become alert faster when aroused from sleep and are easier to arouse from all stages (Lukas, 1973). In this current UMass project, subjects ages ranged from 18-29 years.

Sex differences relative to sleep arousal have also been noted. Lukas and Dobbs (1972), reported that regardless of age, sleep arousal thresholds were lower in women and this varied with age. In a later study, Lukas (1975) noted that college-aged women were less responsive to noise than men, but middle-aged (around 35 years) women were more responsive to noise than middle-aged men. In the UMass Nober et al. study (1980), half of the subjects were female and half male.

Signal significance/cognitive value is not unrelated to "instructions" to subjects (described earlier), but has been investigated separately as a variable. LeVere et al. (1976) found the cognitive value of the stimulus disrupted sleep if it had significance to the individual. Clearly, mothers responded differentially to their own infant's crises. Poitras et al. (1973 reported that 34 days after birth of a child, the mothers' auditory awakening thresholds were lower. Langford et al. (1974) found meaningful stimuli enhanced responses and changed thresholds. Zung and Wilson (1961) doubted that stimulus "significance" or "nonsignificance" per se was important and concluded that "motivation" was the important factor; in the Zung and Wilson (1961) study motivation was financial remuneration. In a later study, Wilson and Zung (1966) did not find sex differences for their "motivated" subjects. In this current UMass project, there was a specific conditioning procedure and remunerative policy.

3. EXPERIMENT A: ACOUSTIC ANALYSES OF SMOKE ALARM SIGNALS

3.1 Objectives

The major aim of Experiment A was to assess the intensity-frequency spectral characteristics of the acoustic signal produced by several popular smoke alert units sold in the United States. Sound pressure measurements were made in an anechoic chamber at 10 feet and 15 feet from the sound source but the room was too small to accommodate 20-foot measurements. In addition, sound pressure measures were made in a 360° directional polar axis, using both an anechoic chamber and a reverberant room. The reverberant room measures were not part of the overall design but were added for reasons to be noted later. The spectral measurements from the anechoic chamber and the reverberant room were analyzed utilizing one octave and one-third octave band analyses. Experiment A also called for measures to be made in several household bedrooms with the door open, the door closed, and in hallway locations.

3.2 Laboratory Locations

Two anechoic chambers were utilized for Experiment A. One of the anechoic chambers is located at the University of Massachusetts, Amherst. The second anechoic chamber and a reverberant room were both located at the Naval Research Medical Laboratory, U.S. Submarine Base, New London, Connecticut.

3.3 Sound Pressure Measurements

Sound pressure level analyses were performed for the acoustic signals of five smoke alarm devices. (Originally 10 units were planned but this did not seem necessary. See Discussion for Experiment A.) Each unit was manually activated and kept in a steady-on state. Acoustic signals were measured in the anechoic chamber at the University of Massachusetts. Sound pressure measures in dBA units were ascertained at 10 and 15 feet from the source, utilizing a Bruel and Kjaer precision Sound Level Meter (Type 2204) with a one-inch condensor microphone (Type 4132).

3.4 Frequency Response Measurements

In this phase of Experiment A, the frequency composition of the smoke alarm signals was examined. Each alarm was manually activated in the anechoic chamber and the resulting acoustic signal was measured using a Bruel and Kjaer Octave-Band Filter (Type 1613) linked to the Bruel and Kjaer Precision Sound Level Meter and the one-inch condensor microphone. Readings were taken at 63, 125, 250, 500, 1000, 2000, 4000, 8000, 16000 Hz, respectively.

Simultaneously, a high quality reel-to-reel tape recording was made of each alarm signal, utilizing a Revox (B77) tape recorder and an Electro-Voice (EV670A) microphone. The acoustic output was analyzed with Bruel and Kjaer Audio Frequency Spectrometer (Type 2112) and a Bruel and Kjaer Graphic Level Recorder (Type 2305). This procedure yielded spectral information in discreet one-third octave bands from 63 to 16000 Hz.

Frequency analyses were also performed in the reverberant room at the New London Naval Medical Research Laboratory. Each of the five smoke alert devices were manually activated and direct one-third octave band readings were recorded. These measurements were made with the Naval Research Laboratory Bruel and Kjaer Audio Frequency Spectrometer and their Bruel and Kjaer Graphic Level Recorder. Spectral measures taken in the reverberant room were later compared to those made in the anechoic chamber at the University of Massachusetts.

3.5 Directional Polar Measurements

Sound pressure measures were taken in a directional plane. The smoke alert units were placed on a specially constructed turntable, with the microphone fixed 10 feet from the turntable at zero axis. The turntable rotated on a 360° axis and the rotation was electronically synchronized to the Bruel and Kjaer Graphic Level Recorder. This procedure resulted in sound pressure measures along a 360° directional axis.

Spectral composition was obtained in the anechoic chamber at the University of Massachusetts. This procedure facilitated recording a set of high quality reel-to-reel tape data that were obtained 10 feet from the source, varying the angle of incidence between the microphone and the smoke alert device. Recordings were made at 15 degree intervals from 0 degrees to 90 degrees. Equipment used in this phase consisted of a Revox B77 tape recorder, Electro-Voice microphone, Bruel and Kjaer Audio Frequency Spectrometer, and a Bruel and Kjaer Graphic Level Recorder.

3.6 Results

Sound level analysis was carried out on five smoke alert devices in the anechoic chamber at 10- and 15-foot distance placements. The measures obtained at 10 feet (Table 1) showed a range from 80 dBA to 92 dBA with a mean of 85 dBA; this mean was consistent with manufacturer specifications. At 15 feet (Table 2) the range was 74 dBA to 87 dBA with the mean at 81 dBA; hence, even at 15, the mean measurement conformed reasonably well to industry and federal expectations.

The spectral analysis compostion of the five smoke alert devices were presented in one octave and one-third octave band analyses obtained from the anechoic and reverberant rooms. Peak energy values consistently occurred at 4000 Hz in the anechoic chamber at 10 feet (Table 1) and at 15 feet (Table 2). Varying microphone-alarm distance did not effectively change the configuration of the spectrum, only decibel values shifted. The low decibel values obtained at 63, 125, and 250 Hz ranged from an indeterminant level that was below 30 dBA to 38 dBA. These values most probably represent low frequency ambient room noise, reportedly an artifact of the UMass anechoic chamber ventilation system (Umass Engineering Lab Report, UMAL 7705, Russell, 1977). Further corroboration of this

Table 1

Smoke Alarm Sound Levels (A-Weighted, dBA) and Octave-Band Frequency Analyses (SPL re .0002 µPascal) Taken 10 Feet from Source in UMass Anechoic Chamber

	Alarm Level		Octave Band Frequency (Hz) SPL (.0002 µPascal)								
Unit #	dBA		**63	125	250	500	1000	2000	4000	8000	16000
101 (GE)	82		36	*< 30	39	39	56	78	83	73	66
102 (Sunbeam)	92		37	< 30	38	59	68	85	87	73	65
103 (First Alert)	80		37	< 30	< 30	< 30	32	60	76	52	36
104 (BRK)	83		37	< 30	35	61	66	71	81	76	66
105 (Chloride Pyrotector)	86		37	< 30	43	50	62	80	82	75	69
AVERAGE	85		37	< 30	32	44	57	75	82	70	60

* <30 dBA designates a Sound Pressure Level (dBA) below the sensitivity of the condensor microphone, the ambient background noise level was approximately 10 dBA (Russell, 1977).

** Measures at this frequency are questionable and probably are the product of a fan noise.

Table 2

Smoke Alarm Sound Levels (A-Weighted, dBA) and
Octave-Band Frequency Analyses (SPL re .0002 uPascal)
Taken 15 Feet from Source in UMass Anechoic Chamber

	Alarm Level		Octave Band Frequency (Hz) SPL (.0002 µPascal)								
Unit #	dBA		**63	125	250	500	1000	2000	4000	8000	16000
101 (GE)	83		40	*< 30	39	44	51	71	81	69	64
102 (Sunbeam)	87		40	< 30	35	56	66	80	83	72	61
103 (First Alert)	74		36	< 30	<30	<30	30	55	70	46	37
104 (BRK)	77		37	<30	32	58	64	66	76	71	59
105 (Chloride Pyrotector)	82		37	<30	31	50	61	78	76	69	63
AVERAGE	81		38	< 30	33	48	54	70	77	65	57

* 30 dBA designates a Sound Pressure Level (dBA) below the sensitivity of the condensor microphone, the ambient background noise level was approximately 10 dBA (Russell, 1977).

** Measures at this frequency are questionable and probably are the product of a fan noise.

suspicion is noted from the nearly identical decibel levels at 10 and 15 feet.

Octave band values are expressed in decibels re: 0.0002 uPascal at 10 feet (Table 1) and 15 feet (Table 2). Energy peaks for all five alarm signals occurred in the 4000 Hz octave band. Another concentration of energy for all five alarm signals occurred in the 2000 Hz band. Most detectors were similar in spectral configuration although one (coded #103) was demonstrably different. This detector produced an alarm signal that was of a narrow band frequency composition. Tables 3 and 4 list the one-third octave values to highlight this response composition of all units more vividly. The narrow band frequency pattern of detector #103 prevailed on the repeated measures taken in the anechoic chamber and reverberant room settings.

In Table 3 (Anechoic Chamber) and Table 4 (Reverberant Room) one-third octave analyses are presented for all five smoke alarm signals. The one-third octave decibel values are relative to the maximum amplitude peak (designated as the zero reference level) for each detector. Hence, all values in Tables 3 and 4 designate the energy levels (in decibels) below the peak zero reference level. Figures 2-6 depict the graphic displays of the one-third octave data for the alarm signals.

Peak energy points were scattered for the alarm signals although a common cluster occurred between 3150 Hz to 6300 Hz. Variability in the peaks appeared somewhat greater in the reverberant room but the overall magnitude was less than in the anechoic chamber, particularly above 5000 Hz for detectors 102, 103, 104, 105. It is difficult to determine from these data the actual fundamental frequencies and harmonies of the alarm signals but they appear to be between 800 Hz to 2000 Hz.

Directional axis analysis data for the comparative directional axes results (Table 5) obtained in the anechoic chamber and reverberant room showed that the amplitude of a smoke detector signal can vary up to 10 dB (re: reference peak amplitude) in the anechoic chamber. Angle of incidence peak differences never exceeded 3.5 dB in the reverberant room. Figure 7 depicts the amplitude differences for the 360° rotation in the anechoic chamber and the reverberant room.

Table 3

Spectral Comparison of Five Smoke Alarm Units
Measured in an Anechoic Chamber - The peak amplitude
frequency in the alarm spectrum was designated
as zero so all decibel notations in this table indicate
the amount of energy below the peak zero reference level.

Relative Amplitude (dB) / Frequency Bands (Hz)	SMOKE ALARM UNITS 101 (GE)	102 (Sunbeam)	103 (First Alert)	104 (BRK)	103 (Chloride Pyrotector)
500	36	22	<40	12	20
630	32	24	<40	29	30
800	22	28	<40	23	32
1000	31	21	<40	2	26
1250	32	26	<40	22	32
1600	17	30	<40	1	23
2000	5	16	30	12	18
2500	14	11	<40	15	26
3150	9	0	0	0	36
4000	0	1	9	9	0
5000	9	2	31	8	5
6300	17	17	<40	6	32
8000	25	15	<40	20	10
10,000	25	22	<40	16	13
12,500	<40	<40	<40	<40	<40
16,000	<40	<40	<40	<40	<40

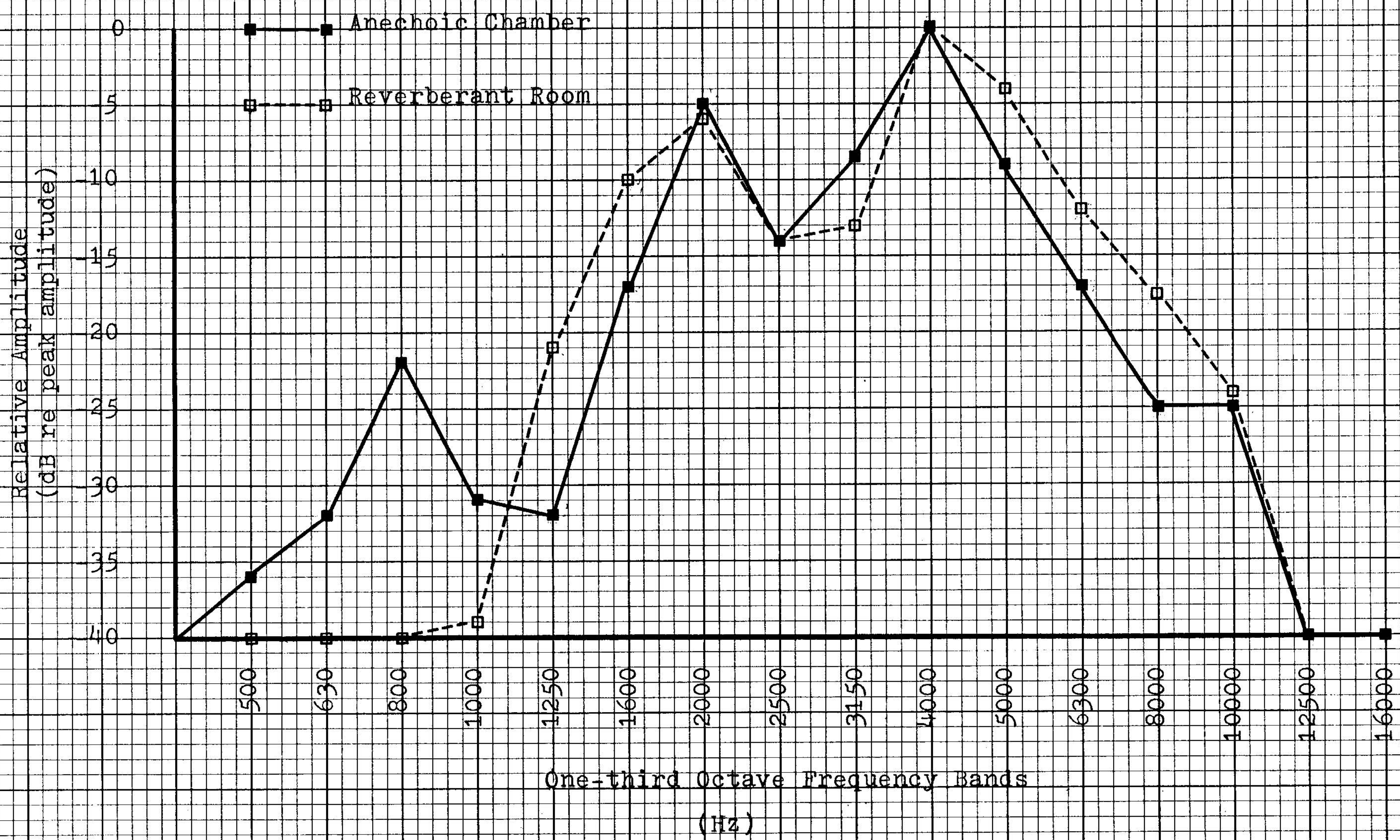
Table 4

Spectral Comparison of Five Smoke Alarm Units Measured in a Reverberant Room - The peak amplitude frequency in the alarm spectrum was designated as zero so all decibel notations in this table indicate the amount of energy below the peak zero reference level.

Relative Amplitude (dB) / Frequency Bands (Hz)	SMOKE ALARM UNITS 101 (GE)	102 (Sunbeam)	103 (First Alert)	104 (BRK)	105 (Chloride Pyrotector)
500	< 40	20	<40	20	<40
630	< 40	< 40	<40	39	30
800	<40	<40	<40	33	34
1000	39	16	<40	11	17
1250	21	30	<40	28	27
1600	10	20	<40	16	13
2000	6	13	30	14	0
2500	14	<40	<40	<40	< 40
3150	13	<40	<40	<40	<40
4000	0	0	0	0	3
5000	4	13	22	13	9
6300	11	<40	<40	<40	<40
8000	18	<40	<40	<40	<40
10,000	24	<40	<40	<40	<40
12,500	< 40	<40	<40	<40	<40
16,000	< 40	<40	<40	<40	<40

Figure 2

One-Third Octave Band Analysis of Smoke Detector 101 Alarm Signal in Anechoic Chamber and Reverberant Room—Central frequency data points are expressed in decibels relative to the peak amplitude, designated as reference zero.



10 Squares to the Inch

Figure 3

One-Third Octave Band Analysis of Smoke Detector 102 Alarm Signal in Anechoic Chamber and Reverberant Room—Central frequency data points are expressed in decibels relative to the peak amplitude, designated as reference zero.

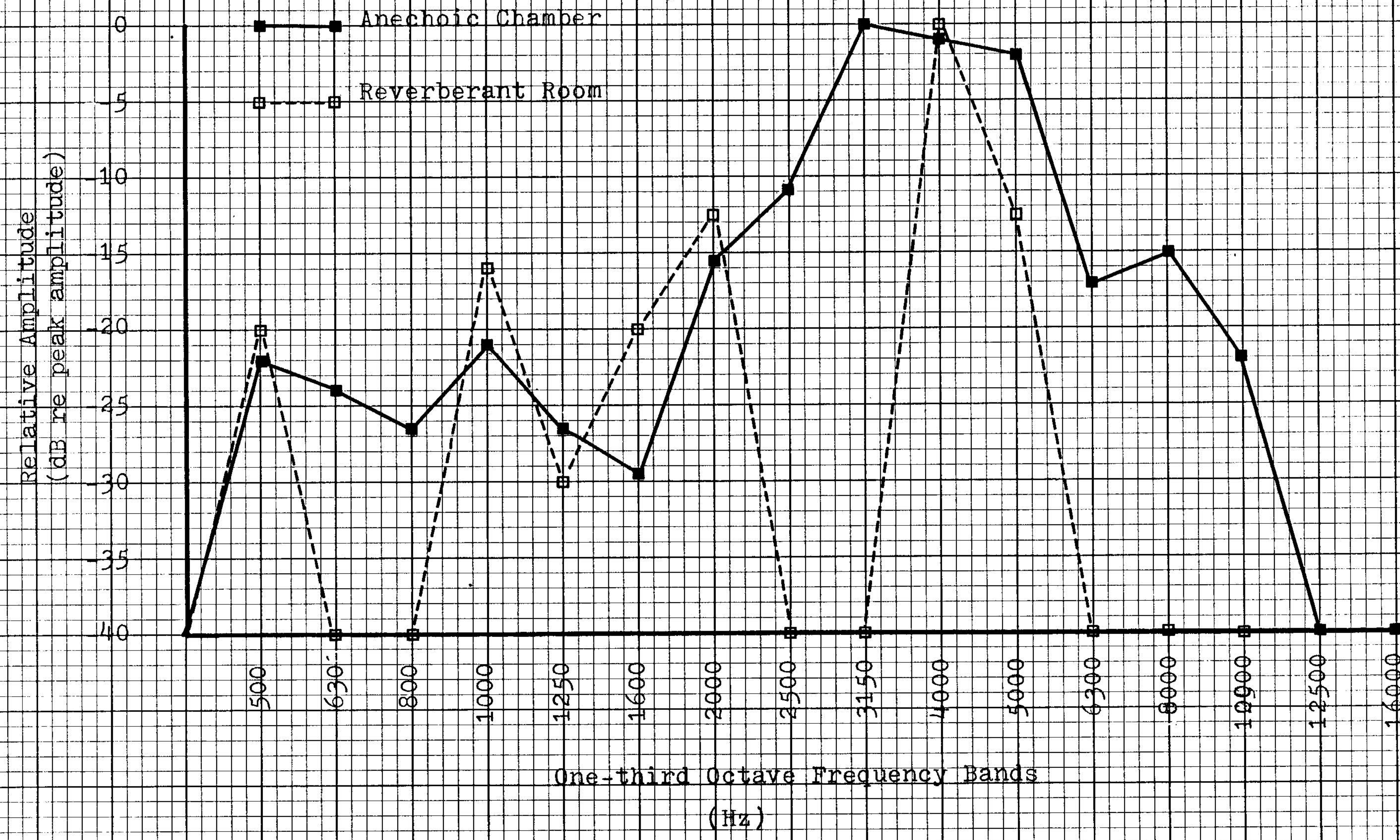


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Figure 4

One-Third Octave Band Analysis of Smoke Detector 103 Alarm Signal in Anechoic Chamber and Reverberant Room—Central frequency data points are expressed in decibels relative to the peak amplitude, designated as reference zero.

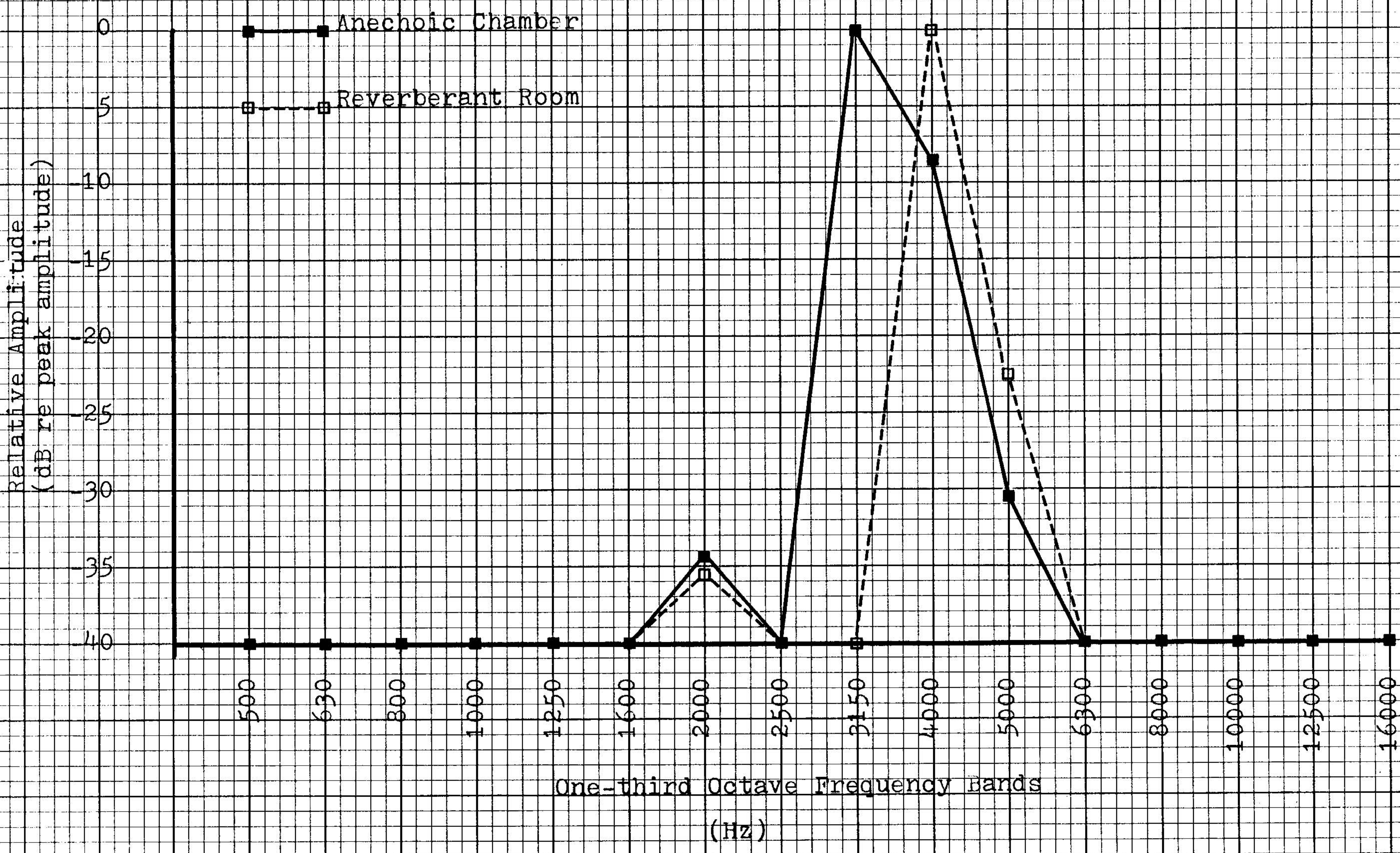

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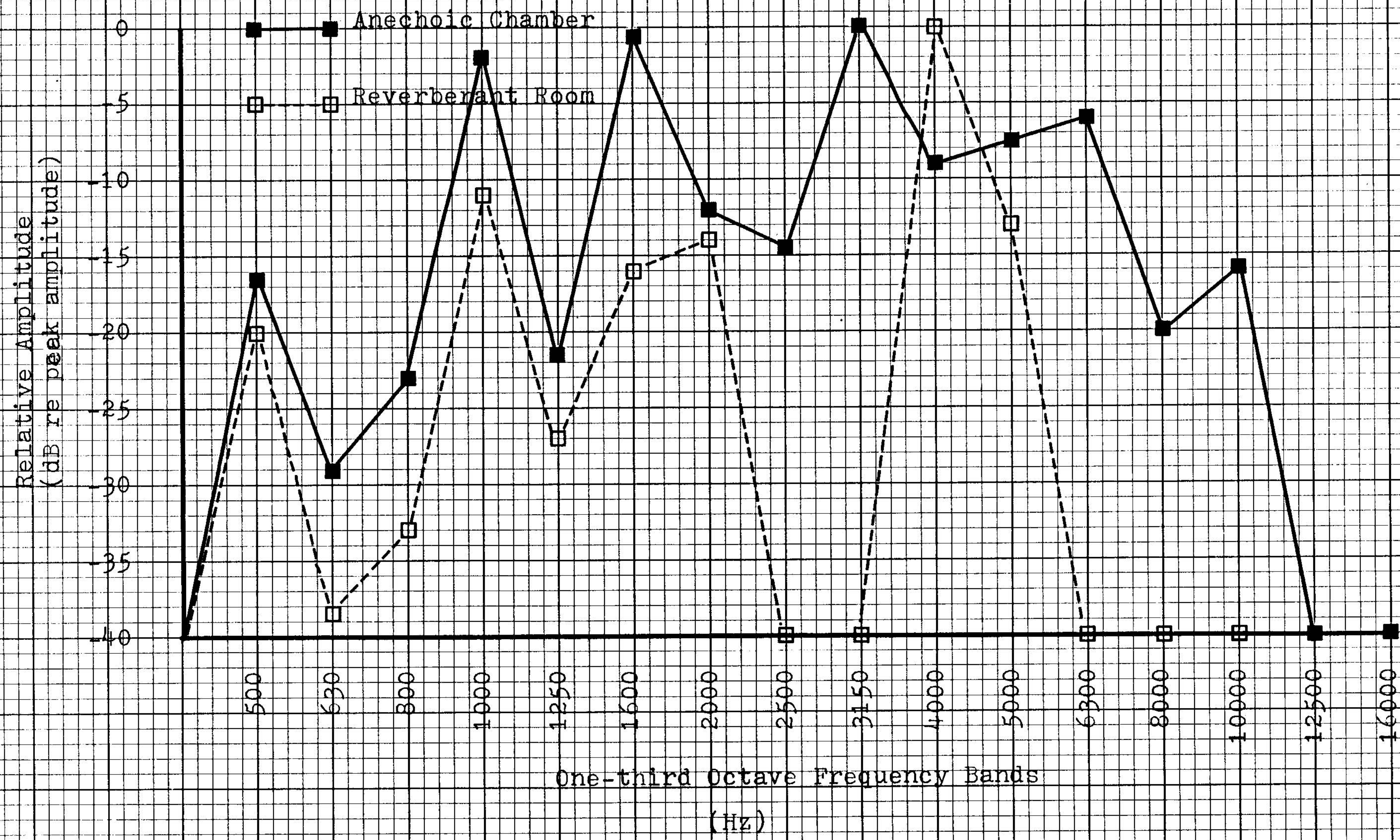
Figure 5

One-Third Octave Band Analysis of Smoke Detector 104 Alarm Signal in Anechoic Chamber and Reverberant Room—Central frequency data points are expressed in decibels relative to the peak amplitude, designated as reference zero.



10 Squares to the Inch

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Figure 6

One-Third Octave Band Analysis of Smoke Detector 105 Alarm Signal in Anechoic Chamber and Reverberant Room—Central frequency data points are expressed in decibels relative to the peak amplitude, designated as reference zero.

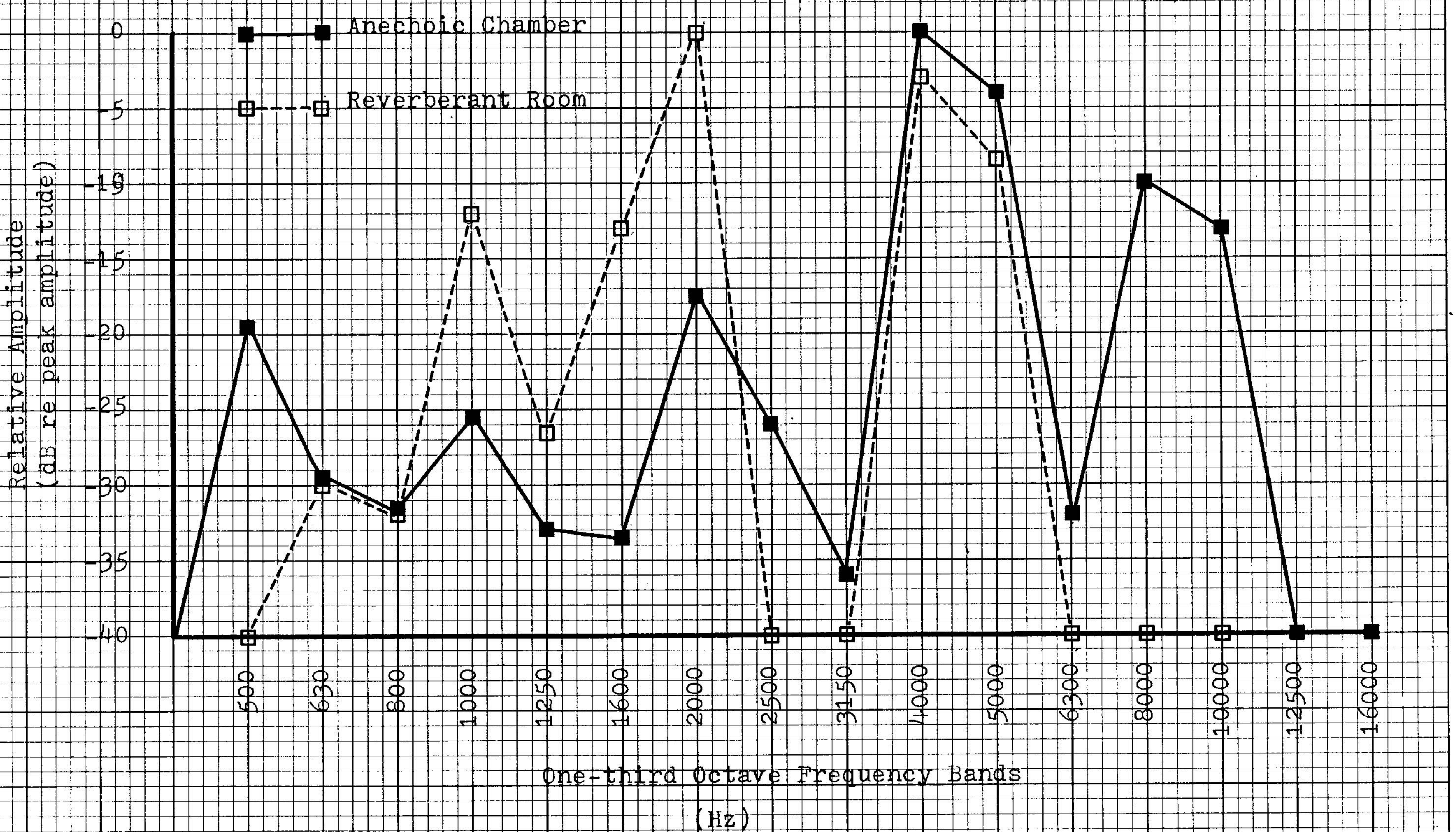

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Table 5

Relative Amplitude of Smoke Alarm Unit 101 (General Electric) in the Direction Axis, in Both the Anechoic Chamber and Reverberant Room (dB re Peak Amplitude Designated as Reference Zero)

Angle of Incidence	Anechoic	Reverberant	Angle of Incidence	Anechoic	Reverberant
0°	0.5	0.5	180°	7.0	3.0
10	0.5	0.5	190	8.5	3.5
20	0.0	1.0	200	7.0	2.5
30	-1.0	1.0	210	5.0	2.0
40	3.0	1.5	220	4.5	1.0
50	5.5	1.5	230	8.0	0.5
60	6.5	1.5	240	10.0	0.0
70	6.0	0.5	250	9.0	2.5
80	5.0	0.5	260	7.0	2.5
90	4.0	0.5	270	5.0	2.5
100	3.5	1.5	280	4.0	2.5
110	3.5	2.5	290	4.0	1.5
120	3.5	2.5	300	5.0	2.0
130	4.0	1.0	310	4.5	1.5
140	5.0	0.5	320	2.0	1.0
150	5.5	0.0	330	0.5	1.5
160	5.0	0.5	340	0.0	1.0
170	5.0	2.5	350	0.5	0.5

Figure 7

Relative SPL Measures of Smoke Detector 101 Alarm on a Polar Plane, in Anechoic and Reverberant Chambers.

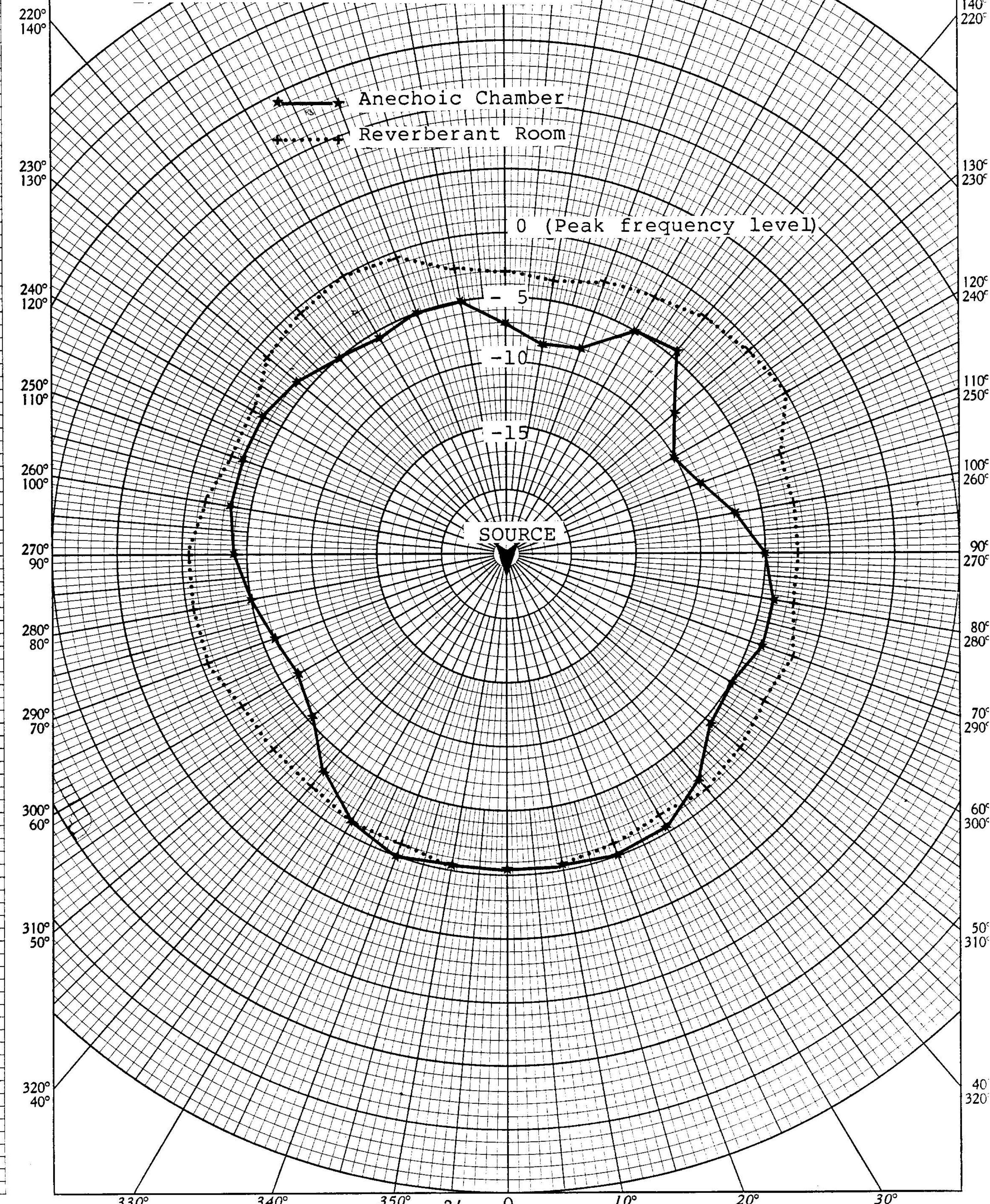
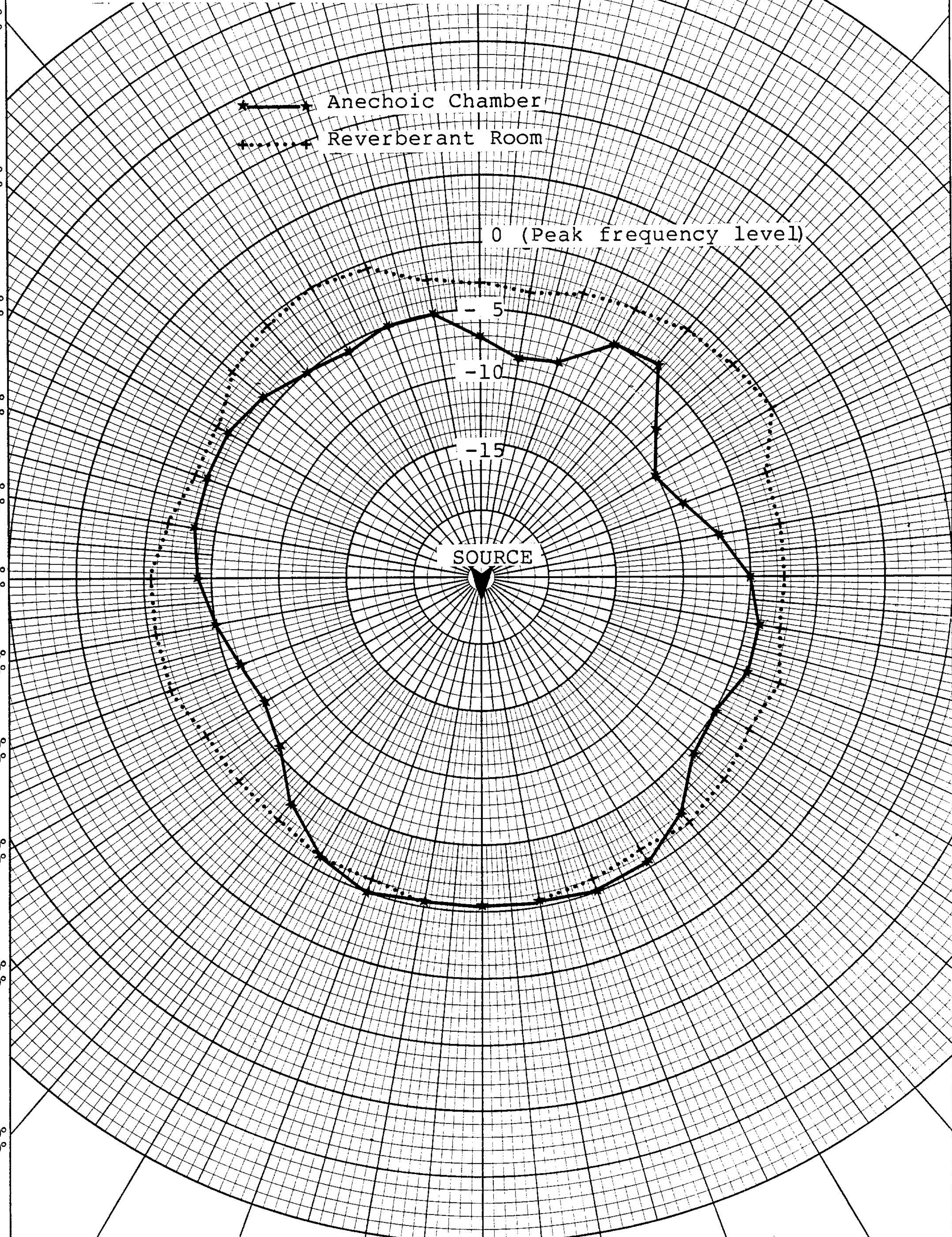


Figure 7

Relative SPL Measures of Smoke Detector 101 Alarm on a Polar Plane, in Anechoic and Reverberant Chambers.



A separate directional axis analysis for smoke detector 101 was conducted from 0 degree to 90 degree angle of incidence (Figure 8). This narrow range of rotation was chosen to parallel household installations made with ceiling or wall mount placements. Measurements were taken at the 0°, 15°, 30°, 45°, 60°, 75°, and 90° axes and plotted in Figure 8. It is noteworthy that the spectral characteristics of the smoke detector signal did not change appreciably for the "mounting" angle of incidence variable. Sound level differences were relatively minor in the dense energy area of the spectrum, i.e., 1600 Hz to 6300 Hz, but somewhat larger at the low and high extremes of the frequency range.

3.7 Discussion

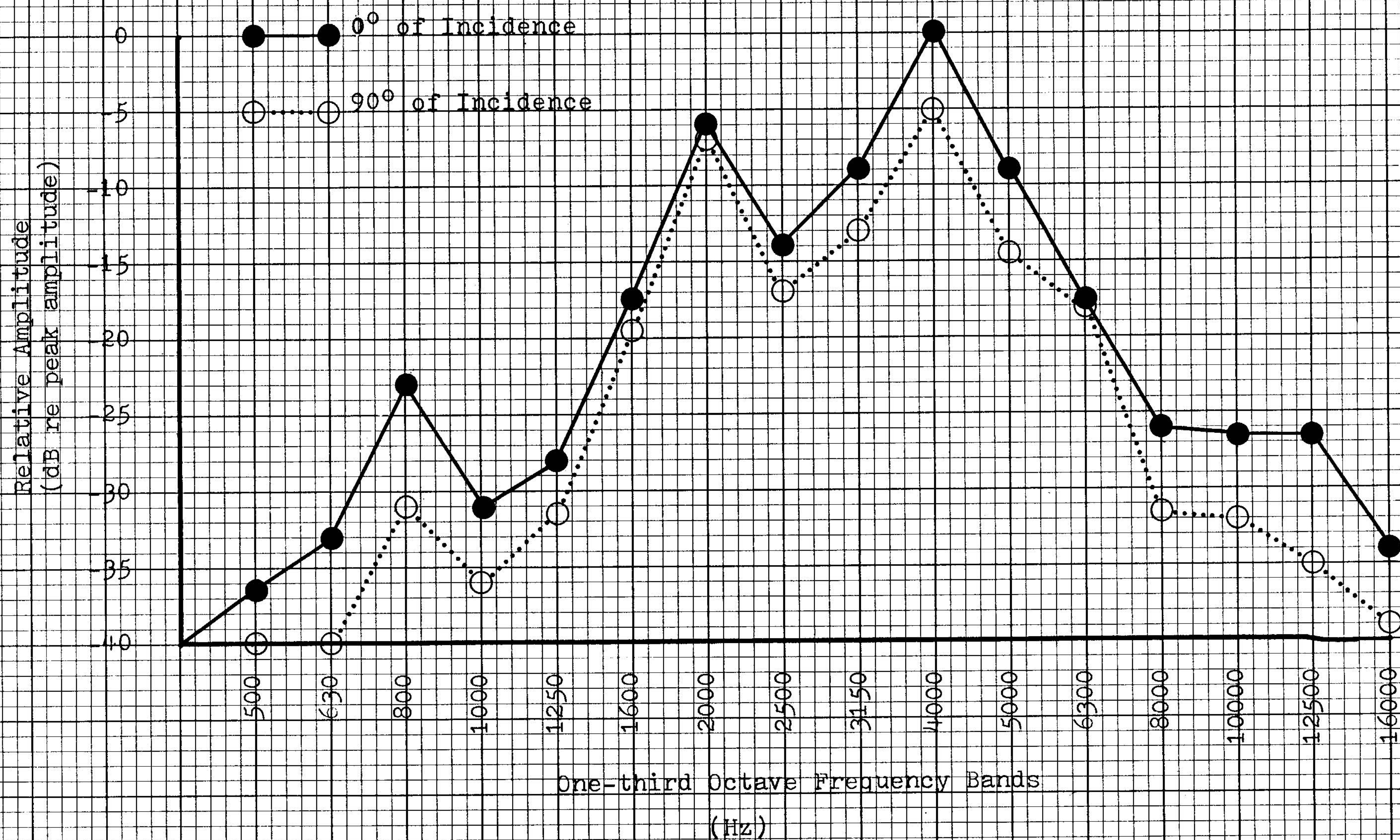
The acoustic comparisons of the effects associated with the anechoic chamber and the reverberant room were not part of the Experiment A proposal. The comparisons were added in response to the relevant Underwriters Laboratories, Inc. Report of April 25, 1979, Industry Advisory Conference for Audible Signal Appliances. This conference dealt with proposed revisions of the "Standard for Audible Signal Appliances, UL 464 . . .and for the Standard for Speakers and Amplifiers for Fire Protective Signaling Systems, UL 1480" to determine the "feasibility of performing speaker audibility and frequency response measurements in a reverberant room rather than in an anechoic chamber." Underwriters Laboratories (UL) presented data which noted a high correlation between the "average value" obtained in a reverberant room and the "peak value" obtained in an anechoic chamber (free field). The UL measures were conducted on a group of loudspeakers.

The data obtained in Experiment A from the anechoic chamber (Table 3) showed the maximum energy peaks in the 3000-4000 Hz band area while the reverberant room measures (Table 4) peaked in the 4000-5000 Hz range. Generally, the reverberant room data showed sharper energy differences in the one-third octave measures in spite of the expectation that a reverberant room would yield a more diffuse field; usually, the reflected waves combine to create a more uniform average energy density throughout the field (Figures 2-6).

It is also expected that the angle of incidence between transducer and microphone in a reverberant room would be inconsequential and more

Figure 8

One-Third Octave Band Analysis of Smoke Detector 101 Alarm Signal at 0° and 90° Angle of Incidence in Anechoic Chamber--Central frequency data points are expressed in decibels relative to the peak amplitude, designated as reference zero.



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significant in the anechoic chamber. Experiment A data (Table 5) was consistent with this expectation as the maximum directionality axes variations were up to 10 dB in the anechoic chamber and never exceeded 3.5 dB in the reverberant room. Practically speaking, these value changes represent relatively minor output changes that may be anticipated between a wall or ceiling smoke detector installation. Household acoustics would modify the projected amounts listed here.

It is noteworthy that Experiment A revealed considerable variances in the one-third octave measurements among the five different smoke detectors and even in measures of different detectors manufactured by the same company. In the latter instance, three detectors from the same company had varying frequency measures. (These data were not part of the study and were not included here). Experiment A data supported the UL May 24, 1979 observation that "the relatively small size and inherent design characteristics of smoke detectors tend to cause nonrepeatability and nonuniform sound output characteristics." As reasons, UL listed variations in sound exit opening configurations among manufacturer's units, internal construction variations and harmonic content variations among models. Because the UMass investigators observed this variance, part of Experiment A was finally completed using five smoke detectors rather than the 10 detectors originally projected. Additional time was devoted to the inclusion of comparative polar directionality measurements in the highly absorbent anechoic chamber and the reflective reverberant room — the latter ostensibly more representative of general household conditions than the former.

4. EXPERIMENT B: SUBJECT RESPONSE TO SMOKE DETECTOR ALARM SIGNAL

The overall objective of Experiment B was to elicit a profile of the waking effectiveness of the smoke detector alarm signals at 55, 70, 85 dBA using young, normal hearing college-aged subjects. Each sound level condition tested 10 subjects, or a total of 30 different subjects.

4.1 Subjects for Experiment B

The schedule for Experiment B considered work days, weekend days, sex distribution and the target hour. All 30 subject respondents were between 19-29 years, inclusive. Final participation arrangements were made by telephone and the equipment was installed at a convenient subject time. At installation time, the pure tone hearing screening test (see Appendix A) and the pre-trial questionnaire were administered (see Appendix B). Also, the one person serving as the formal respondent in each residence underwent the pre-test subject alarm conditioning procedure. Conditioning trials included hearing the tape for three alarm trial presentations at 55 dBA, three trial presentations at 70 dBA and three trials at 85 dBA — a total of nine trials in random order. All three levels were used for conditioning to minimize potential stimulus generalization bias associated with any repeated signal test level. On the day following the alarm presentation trial, the post-questionnaire form was completed. (See Appendix C for details of the questionnaire items.) Only the volunteer respondent designee was permitted to complete the pre- and post-questionnaires, to shut-off the alarm signal when awakened (shut-off latency), to telephone the fire department (phone-call latency). In the event another household occupant awakened first, he/she was permitted to awaken the respondent. The respondent received the $25.00 honorarium and the personal smoke detector (see Appendix D). All subjects had normal hearing sensitivity. Air conduction hearing screening was given at 10 dB for 500, 1000, 2000, 4000, 8000 Hz in each ear just prior to installation to ensure criteria eligibility.

Participants for this experiment were drawn from the extended University of Massachusetts community. Homes were located in Amherst and surrounding areas. Initial contact with the subjects was made through local media (newspaper advertisement, University Bulletin, radio interviews and by word of mouth).

4.2 Instrumentation for Experiment B

The alarm programming system was constructed and pre-tested for accuracy. This system was assembled as follows:

> The alarm program assembly was wired into an Intermatic (V4717) timer. The alarm signal was

delivered to the respondent via a tape recording played from a Revox (B77) through a Marantz 2265B amplifier to a Marantz 770 speaker. The Revox tape recorder was set in the "play-pause" position until the targeted day and hour. Then the timer released the pause control and all timers, signals, etc., were activated. During the 1-5 day experimental waiting period, amplifier and a "real-time" clock were continuously powered.

The subject's instruction was to deactivate the alarm by pressing a response key. A second clock was synchronized to record elapsed time from "alarm-on to alarm-off" (stimulus presentation period). Furthermore, when the response key was activated by the subject, all equipment and clocks were shut off (see Figure 9). As a precaution, the entire assembly deactivated automatically in the event of an inadvertant power failure. Subjects had instructions to contact the experimenter in such an event.

The experimental equipment was divided into two location placements in the subject's home. The loudspeaker and response key were measured and placed 10 feet from the respondent's bed. The remaining equipment was set up in a different room. This arrangement of equipment shielded the subject from hearing extraneous noises produced by the tape recorder, amplifier or timer as they were activated. Except for a few early minor equipment failures during pre-tests this system worked almost flawlessly.

4.3 Amherst Fire Department Participation

Arrangements were coordinated with the Amherst Fire Department (Appendix E). When the experimental subjects were awakened by the taped detector alarm signal, they first had to turn off the alarm signal and then telephone a special direct number to the fire department. Subjects identified themselves by project identification, "Project Detector" (see Appendix F). Project identification was included so that the dispatcher would not discharge fire engines to the residence. Apart from project identification, the fire dispatcher asked the standard series of questions used under normal circumstances (see Appendix G). Since the Amherst Fire Department telephone is connected to a computer, conversations were automatically taped and timed. Thus, phone call

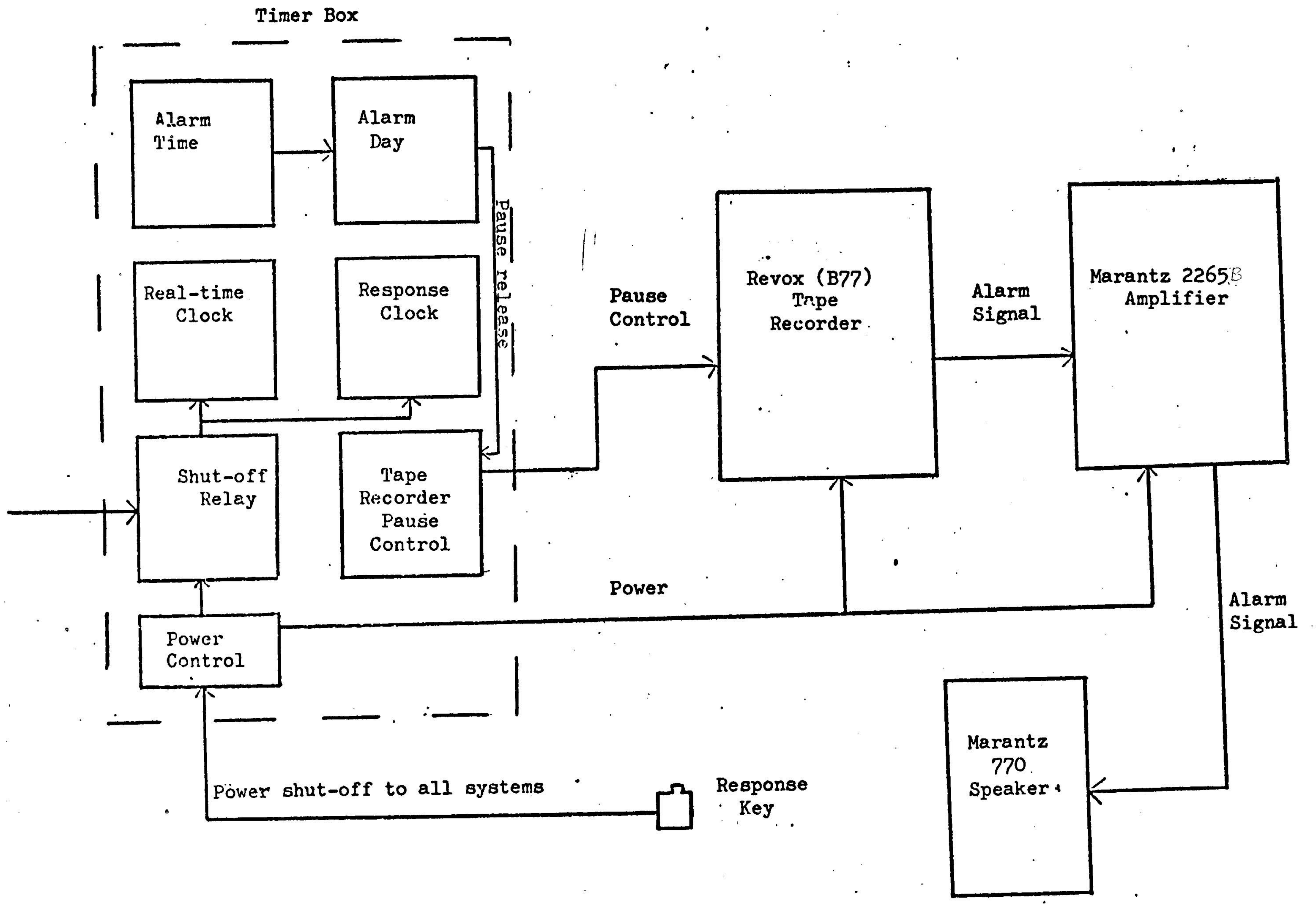

Figure 9

Block Diagram of Alarm Control Program and Subject Response System.

latency was answered by comparing the time a phone call was initiated to the reading on the subject's timer box.

4.4 Data Analysis of Questionnaires

As stated earlier, pre- and post-alarm questionnaires were given to each subject. Including the set of response times, there were 49 separate data items for each respondent (Appendices C and D). Since, however, some of these measures were redundant, only 30 variables were retained for analysis (Table 6).

Several statistical analyses were conducted. Initially, simple *t*-tests were used to make pairwise comparisons between the different alarm level groups. These analyses were conducted on all 30 dependent variables in order to determine whether differences between groups could be attributed to factors other than alarm level. In addition, a matrix of Pearson correlation coefficients was obtained, primarily to determine whether any factors tapped by questionnaire items could be used to predict response latency. Finally, in some conditions (especially at 55 dBA in *Experiment Bacn*), multiple regression was used in an attempt to investigate whether there were any factors tapped by the questionnaire that reliably discriminated between fast and slow respondents or other household occupants. Given the rather large number of variables and the modest number of subjects, the results of the multiple regression analyses must be considered as being only suggestive.

4.5 Results of *Experiment B*

The data for the 30 subjects in *Experiment B* (Table 7) showed respondent shut-off latencies (measured from when the alarm went on to when the respondent shut off the apparatus) were 13.60 seconds, 9.50 seconds and 7.40 seconds as 55, 70 and 85 dBA, respectively. A summary of *Experimental B* means (Table 8) showed the average mean (55 and 70 dBA levels pooled) to be 11.5 seconds for *Experiment B* subjects. *T*-tests (Table 9) revealed significant differences between the 55 dBA (13.60 seconds) and 70 dBA (9.50 seconds) means (p=.038); between the 55 dBA (13.60 seconds) and 85 dBA (7.40 seconds) mean (p=.002). However, there was no significant difference between the 70 dBA and 85 dBA means. When the 55 dBA mean was compared to the mean of the pooled 70 dBA and

Table 6

Dependent Variables Used in Analyses

Variable	Questionnaire Item Number	Variable Name
1	--	"Shut-off latency"
2	--	"Phone-call latency"
3	--	Time required to reach phone when awakened
4	--	Hours asleep when alarm sounded
5	--	Number of days from installation
6	Pre-1	Sex of respondent
7	Pre-1	Age of respondent
8	Pre-3	Number of people in respondent bedroom
9	Pre-2	Apartment or house
10	Pre-4	Pet, yes or no
11	Pre-5	Area of residence (town, city, rural)
12	Pre-13	Subject's rating of nighttime noise
13	Pre-14	Frequency of sleep disruption, windows closed
14	Pre-15	Frequency of sleep disruption, windows open
15	Pre-16	Subject's self-rating estimate of sleep soundness from very light to very heavy
16	Pre-17	Sleep routine (regular or irregular sleep)
17	Pre-19	Average hours of sleep/night under normal conditions
18	Pre-20 or 21	Number of times awakened per night under normal conditions
19	Pre-22	Alcohol or drug use at night, prior to sleep
20	Pre-22	Frequency of alcohol or drug use prior to sleep
21	Pre-23	Frequency of use of air-conditioner or fan in warm weather
22	Pre-24	Frequency of use of TV or radio in bedroom at night
23	Pre-25	Frequency with which sleep occurs with TV/radio playing
24	Pre-27	Subject's pre-test confidence in being awakened by alarm
25	Post-1	Were others awakened by alarm?
26	Post-4	Coherency rating of respondent upon being awakened by alarm
27	Post-9	Respondent tiredness rating on alarm night
28	Post-10	Competing noise (e.g., TV, horn) present during alarm activation
29	Post-15	Sensitivity to presence of equipment
30	Post-16	Subject's post-test confidence in being awakened by alarm

Table 7

Subject Performance to Three Smoke Detector Sound Levels at Ear/Pillow Position—Experiment B

55 dBA					70 dBA					85 dBA				
Ss#	Sex	Shut-off Latency (sec)	Phone Call Latency (sec)	Total Latency (sec)	Ss#	Sex	Shut Off Latency (sec)	Phone Call Latency (sec)	Total Latency (sec)	Ss#	Sex	Shut Off Latency (sec)	Phone Call Latency (sec)	Total Latency (sec)
1	M	05	54	59	11	M	04	33	37	21	F	08	16	24
2	M	15	38	53	12	F	08	26	34	22	F	05	30	35
3	F	16	33	49	13	F	11	31	42	23	F	04	76	80
4	F	10	68	78	14	F	09	60	69	24	F	11	98	109
5	F	09	75	84	15	M	07	41	48	25	F	10	42	52
6	M	15	59	74	16	M	14	68	82	26	M	09	30	39
7	M	15	46	61	17	M	09	106	115	27	M	08	70	78
8	F	12	57	69	18	F	09	44	53	28	M	09	44	53
9	F	18	40	58	19	M	08	30	38	29	M	04	20	24
10	M	21	94	115	20	F	16	80	96	30	M	06	36	42
Mean		13.60	56.40	70.00	Mean		9.50	51.90	61.40	Mean		7.40	46.20	53.60
St. Dev.		4.43	17.81	18.38	Std. Dev.		3.76	24.83	27.00	Std. Dev.		2.37	25.27	26.10
Range		05-21	33-94	49-115			04-16	26-106	34-117			04-11	16-98	24-109

Table 8

Mean Time (seconds) to Shut Off Apparatus in Experiments B, Bacn, and Bvcr

		Detector Alarm Level			
Experiment	Ss N	55 dBA	70 dBA	85 dBA**	Alarm levels 55, 70 dBA pooled
B (Alarm signal only)	30	13.60	9.50	7.40	11.55
Bacn (Alarm signal plus air-conditioner noise)	20	43.43*	18.80	not tested	28.94
Bvcr/TV (Alarm signal plus video taped movie)	20	9.50	5.80	not tested	7.65

* Data based only on subjects who responded within 240 seconds; thus, subjects #4, #8, #9 were treated as a separate group.

** Not included in pooled means.

Table 9

T-Test Results for Experiments B, Bacn, Bvcr
(Dependent Variable: Time to Shut-Off Apparatus)

Variables	df	t-Value*	Significance Level
Alarm only (Experiment B) (dBA groups)			
55 vs. 70	18	-2.23	.038
55 vs. 85	18	-3.70	.002
70 vs. 85	18	-1.56	.136
55 vs. 70 & 85	28	-3.60	.001
Air-conditioner only (Experiment Bacn)			
55 vs. 70 (omitted 3 Ss)	15	-1.79	.094
55 vs. 70 (included NR)	18	-2.60	.018
VCR only (Experiment Bvcr)			
55 vs. 70	18	-2.21	.040
Alarm only (Experiment B) vs. Alarm and AC (Experiment Bacn)			
55 vs. 55	15	2.82	.013
55 vs. 70	18	0.69	.502
70 vs. 70	18	1.24	.232
70 vs. 55	15	3.23	.006
55 & 70 vs. 55 & 70	35	2.58	.014
Alarm only (Experiment B) vs. Alarm and VCR (Experiment Bvcr)			
55 vs. 55	18	-2.00	.060
55 vs. 70	18	-4.74	.001
70 vs. 55	18	0.00	1.000
70 vs. 70	18	-2.63	.017
55 & 70 vs. 55 & 70	38	-2.86	.007
Alarm and AC (Experiment Bacn) vs. Alarm and VCR (Experiment Bvcr)			
55 vs. 55	15	-3.22	.006
55 vs. 70	15	-3.59	.003
70 vs. 55	18	-1.23	.235
70 vs. 70	18	-1.73	.100
55 & 70 vs. 55 & 70	35	-3.17	.003

*Positive value indicates that second group compared had longer latency and negative value indicates that first group had longer latency.

85 dBA group, the difference was highly significant ($\underline{p}$=.001). Clearly, at 55 dBA, subject shut-off response time to the alarm signal was longer than shut-off response time at 70 and 85, or the average of the latter two means.

Mean response relative to the phone call to the Amherst Fire Department were 70.00 seconds at 55 dBA, 61.60 seconds at 70 dBA and 53.60 seconds at 85 dBA.

Variability in the times taken to shut-off the apparatus and phone the fire department was smallest at 85 dBA. Total performance time was less than one minute in most instances, and never exceeded two minutes.

It is clear that the rapid subject responses represent performance by a motivated population of young adult volunteers, somewhat sensitive to experimental research studies. While the test environment was field-based at the subject's home, the subtle implications of the instructions, the visual and physical presence of the apparatus, the expectation of an alarm to be activated during a constrained seven-day range and a six-hour sleep-window, a self-driven desire to respond well — all collectively must have influenced the sensitivity set of the subjects to yield this highly tuned in level of performance.

4.6 Questionnaire Results

Several interesting relationships were revealed by analyzing the measures of latency and the dependent variables of the questionnaire. Two variables related to (1) shut-off latency and (2) phone-call latency while 25 items dealt with a variety of factors such as subject habits, household and environmental conditions, sleep characteristics, alarm presentation and experimental variables, etc. (Table 6). A cluster of variables surfaced that suggested "heavy" sleepers identified themselves accurately as they took longer to awaken from the alarm (at either the 55 or 70 dBA levels) and longer to shut off the equipment and telephone the fire department. Confidence that the alarm signal would be effective, as rated by subjects on the pre- and post-questionnaires was also consistent with their self-concept of "light" and "heavy" sleep characteristics. It is important to reiterate and stress that the data should be interpreted conservatively since the samplings were small and a large number of variables were considered. A brief summary of the significant correlations revealed that the self-rated "light" sleepers awakened faster than self-rated "heavy" sleepers ($\underline{r}$=.38; $\underline{p}$=.018); conversely, "heavy" sleepers took longer to arouse than "light" self-rated sleepers — indicating accurate self-rating predictions. This accuracy for self-rating was also reflected in the pre-questionnaire confidence rating for waking-time and response-time. Subjects who were confident of being awakened by the detector alarm signal did respond faster ($\underline{r}$=.38; $\underline{p}$=.019). Moreover, subjects who responded faster indicated increased confidence in smoke detectors on the post-questionnaire ($\underline{r}$=.45; $\underline{p}$=.006). There was also a relationship between self-rated "coherence" when awakened and shut-off time; the faster the subjects awakened, the more coherent they rated themselves ($\underline{r}$=.37; $\underline{p}$=.021). There was also a significant tendency ($\underline{r}$=.35; $\underline{p}$=.028) for shut-off time to be negatively correlated with the frequency with which people reported they were normally awakened by outside noise. In other words, the more interrupted the sleep, the faster the responses to alarm signal shut-off. Subjects with radios and TV sets in their bedrooms that were normally played prior to sleep had faster responses to shut-off ($\underline{r}$=.32; $\underline{p}$=.041) and people with air-conditioners normally running also had faster responses ($\underline{r}$=.34; $\underline{p}$=.034). There was no waking correlations with sex of respondent or with length of time equipment was installed in home.

<u>All</u> of the above was consistent with tendency for heavier sleepers to take longer to respond and consistent with some of the studies reported in the literature. It is not surprising that subjects responded to the 55 dBA tone (Bradley and Meddis, 1974; Shapiro et al., 1963) — assuming they were self-motivated (LeVere et al., 1976) and internally primed to respond with dispatch (Zung and Wilson, 1961). Several studies reported sleep arousal to 55 dBA or less. Also cited in the literature, and in part supported in this study, are motivational influence, an ability of some people to self-awaken at predetermined target hours, selective auditory monitoring and discrimination during sleep — especially for meaningful stimuli (Langford et al., 1974).

Because the subject responses were so rapid in <u>Experiment B</u>, another brief exploration was conducted to determine the levels radio alarms were normally set by the same people to awaken themselves. Hence, the sound levels for 15 alarm radios were measured for about half of the subjects in Experiment B. Results showed a mean self-setting of 61 dBA at pillow level with a range of 40 to 85 dBA. Actually, seven of the radio alarm settings yielded data between 53-59 dBA, curiously close to the 55 dBA alarm parameter. Thus, daily waking arousal alarm volume is normally set at relatively low levels. Radio alarms were tested instead of clock alarms since the former allows the subject to adjust his/her own setting while most clock alarms are fixed.

5. EXPERIMENT BACN: SUBJECT RESPONSE TO ALARM SIGNAL IN THE PRESENCE OF AIR-CONDITIONER NOISE

Experiment Bacn assessed the waking effectiveness of the detector alarm signal in the presence of an air-conditioner noise (acn) background. The procedures and task requirements were essentially the same as used in Experiment B with the exception that subjects in Experiment Bacn received a continuous taped air-conditioner noise from 8:00 p.m. to 6:00 a.m. nightly on a Teac 601 reversible cassette tape recorder. In accordance with current acoustic data on air-conditioner noise provided by a nationally reputed organization, a representative window air-conditioner noise in high-fan-cool mode was taped and amplified to 63 dBA measured 12 inches from the speaker source placed near a window. The detector alarm setup remained as described for Experiment B (see Figure 9 for the block diagram).

Only the 55 dBA and 70 dBA alarm levels were used in Experiment Bacn since the rapid waking arousal and performance at the 70 dBA alarm level precluded the need to test at the 85 dBA level. Furthermore, since it was apparent from the Experiment B data that the day-of-week and time-of-night variables revealed no significant performance effect on response latencies, all 20 Experiment B subjects (10 at 55 dBA and 10 at 70 dBA) received the detector alarm near 3:30 a.m.

5.1 Results

Data from Experiment Bacn at the 55 dBA alarm level are presented in Table 10. While the air-conditioner noise level was sustained at 63 dBA (window location placement), the levels at pillow (ear) position (column D) diminished depending on room acoustics, room size, bed distance, carpeting, furniture, etc.

Table 10

Subject Performance to the 55 dBA Smoke Detector Alarm Sound Level with Background Air-Conditioner Noise — Experiment Bacn

		A	B	C	D	E	F
					Air-Conditioner Level		
Ss#	Sex	Shut-off Latency (sec)	Phone Call Latency (sec)	Total Latency (sec)	A/C at Pillow	Alarm at Pillow	S/N Ratio
1	F	62	31	93	48	55	7
2	M	75	62	137	50	55	5
3	F	11	34	45	50	55	5
4	M	(No Response)	(No Response)	(No Response)	54	55	1
5	F	07	30	37	48	55	7
6	M	06	41	47	51	55	4
7	M	72	44	116	53	55	2
8	F	(433)	(36)	(469)	51	55	4
9	F	(No Response)	(No Response)	(No Response)	50	55	5
10	M	71	53	124	53	55	2
Mean		43.43*	42.14*	85.57	50.8	55	4.2
Std. Dev.		30.93*	11.05	37.57			
Range		06-75*	31-53	45-137			1 to 7

* Data based only on subjects who responded within 240 seconds; thus, subjects #4, #8, #9 were treated as a separate group. Subject #4 and #9 did not wake up during the alarm period and subject #8 took more than seven minutes to respond. A four minute (240 second) maximum was used for data analysis since this period is generally considered the upper limit for a safe evacuation during a fire.

Column D lists the actual sound levels recorded at ear level, sound level meter positioned on the pillow; column E presents the smoke alarm levels at pillow location. Finally, the signal-to-noise ratio of the alarm signal to air-conditioner noise at pillow location are presented in column F.

Waking response latencies for the 10 subjects are listed in Column A. Two subjects (#4, #9) never awakened to perform the tasks and one subject (#8) required 433 seconds. The maximum program on the tape for the tone was 600 seconds but 600 seconds was not recorded for the "no-response" subjects since it would skew the data of the subjects who did waken and respond. Actually, for data analysis, a 240-second maximum was used since this period is generally regarded as the upper limit for a safe evacuation during a fire. Hence, subject #8 was not included in the *t*-test analysis but treated separately in the correlation analysis with subject #4 and #9 who never awakened.

Waking response latencies for the alarm are listed in column A, Table 10. The seven subjects calculated for the analysis had a mean response of 43.43 seconds with a range from six seconds to 75 seconds. For the 55 dBA alarm, the mean shut-off time of 43.43 seconds in Experiment Bacn was significantly longer (p=.013) than the mean shut-off of 13.60 seconds in Experiment B (Table 7). It must be stressed that while the 43.43 second value was a statistically longer response period than 13.60 seconds, the former was still less than a minute in absolute time even with an average S/N ratio of 4.2 dBA. Furthermore, 43.43 seconds represents the constrained estimate of only the subjects who awakened within four minutes, but 20% did not awaken in Experiment Bacn and one subject required 433 seconds, nearly 7 1/4 minutes. In contrast, all 10 subjects awakened in the unmasked condition of Experiment B. It is noteworthy to reaffirm that the average S/N ratio was 4.2 dBA at the 55 dBA level.

For the 70 dBA alarm (Table 11), the mean subject shut-off latency was 18.80 seconds with a range from 6-85 seconds. The mean alarm level to air-conditioner level S/N ratio was 21.0 dBA. A *t*-test between the 55 dBA mean (43.43 seconds) and the 70 dBA mean (18.80 seconds) was not significant (p=.094) when the three "no response" subjects were omitted, but the differences were highly significant (p=.018) when the three

Table 11

Subject Performance to the 70 dBA Smoke Detector Alarm Sound Level with Background Air-Conditioner Noise — Experiment Bacn

		A	B	C	Air-Conditioner Level D	E	F
Ss#	Sex	Shut-off Latency (sec)	Phone Call Latency (sec)	Total Latency (sec)	A/C at Pillow	Alarm at Pillow	S/N Ratio
1	F	85	34	119	51	70	19
2	F	16	88	104	47	70	23
3	M	13	59	72	49	70	21
4	F	06	53	59	46	70	24
5	M	12	73	85	48	70	22
6	F	11	52	63	50	70	20
7	M	15	59	74	49	70	21
8	F	09	27	36	50	70	20
9	M	06	54	60	49	70	21
10	M	15	37	52	51	70	19
Mean		18.80	53.60	72.40	49.0	70	21.0
Std. Dev.		22.38	17.29	23.44			
Range		06-85	27-88	36-119			

were included using the maximum 240 second cut-off value (see footnote in Table 10). Thus, it can be said, subjects responded faster when the S/N ratio was 21.0 dBA rather than 4.2 dBA.

T-tests (Table 9) were also performed between Experiment B means (alarm only) and Experiment Bacn (alarm and AC noise). When the 13.60 seconds mean (55 dBA alarm only) was compared to the 43.43 seconds mean (55 dBA alarm and AC noise) the former was significantly shorter (p=.013) whereas 55 dBA alarm only (13.60 seconds) vs. 70 dBA alarm and AC noise (18.80 seconds) means did not significantly differ. The 70 dBA alarm only mean vs. the 55 dBA alarm and AC noise mean significantly differed (p=.006) but not 70 dBA alarm only vs. 70 dBA alarm and AC noise. Significant differences occurred (p=.014) when the pooled (55 and 70 dBA) value of alarm alone (Experiment B) was compared to the pooled value for alarm plus AC noise (Experiment Bacn).

Correlation analysis revealed patterns similar to the data reported for Experiment B. Rated confidence in smoke detectors as determined by pre-trial (r=-.47; p=.018) and post-trial (r=-.71; p=.001) questionnaires correlated negatively with shut-off latency. People who woke up more quickly also tended to rate themselves as being significantly more coherent (r=-.60; p=.003) upon awakening.

The 55 dBA condition of Experiment Bacn was thought to be particularly important since two subjects (20 percent) failed to awaken and a third (10 percent) failed to awaken in the four-minute (240-second) period established as maximum period for data that would be used in the analyses. (Note: The actual alarm on tape sounded for a full 10 minutes/ 600 seconds.) While the third subject did awaken during the 600-second alarm presentation, for the purpose of analyses he was treated as a non-responder since he exceeded the 240-second limit.

Inspection of the response data of the 10 subjects in Experiment Bacn, 55 dBA (Table 10) will show it was experimentally convenient to designate three groups: Group 1, the "fast" group, had a mean response of 8 seconds and consisted of subjects #3 (11 seconds), #5 (7 seconds, #6 (6 seconds). Group 2, the "medium" group, had a mean response of 70 seconds and consisted of subjects #2 (75 seconds), #7 (72 seconds), #10 (71 seconds), #1 (62 seconds). Group 3, the "no response" group, consisted of subjects #4 and #9 who never awakened and #8, who awakened in

433 seconds but was entered as a "no response" for statistical computation purposes since the sampling population size was modest.

In an attempt to determine whether any of the dependent variables could predict which subjects would fall into the three groups a stepwise multiple regression was performed with group assignment (1, 2, 3) as the dependent variable. (The authors, aware of the caveats pertaining to such analyses with small numbers of subjects, offer these findings as suggestive.) The first two variables entered into the equation (accounting for 89% of the variance) were frequency of being awakened at night and how long subjects had been asleep (time-into-sleep) when the alarm was sounded.

Group 1 (fast-response subjects) consistently reported normally awakening an average of one time-per-night as a regular pattern while the other two groups never or rarely awakened during the night, particularly for physiological reasons.

Group 3 ("no-response" subjects) averaged 90 minutes into sleep when the alarm was activated. By contrast, the Group 1 subjects averaged 190 minutes into sleep when the alarm sounded; the Group 2 (medium-fast subjects) were 233 minutes into sleep. Hence, the "no-response" group only 1 1/2 hours into sleep was consistent with some of the literature which reported greater resistance to arousal from sleep during this period. Since the alarm always sounded at 3:30 a.m., and the "no-response" subjects had retired very late, it is not clear whether the critical factor is "time-into-sleep" or how late the subject stayed up.

Finally, as indicated in the other analyses, the faster subjects (Group 1) also had the highest pre- and post-test questionnaire self-confidence ratings while the slowest "no-response" subjects (Group 3) had the lowest pre- and post-test questionnaire self-confidence ratings.

6. EXPERIMENT BVCR: SUBJECT RESPONSE TO ALARM SIGNAL WHILE VIEWING VCR TELEVISION

The third component of the behavioral subject performance experiments, Experiment Bvcr, provided data on subject response latency while viewing a video tape recorded television movie ("Godfather II") at bedtime. But this experimental component had two noteworthy departures in experimental design from Experiments B and Bacn. One notable departure in Experiment Bvcr represents the only instance when subjects were actually programmed to be awake when the alarm signal became activated. The second major departure in the experimental design was that each respondent was allowed to set the TV monitor volume dial to his/her own "most-comfortable-listening level," hopefully to simulate normalcy. The required response was essentially the same as for Experiment B and Bacn. However, for Experiment Bvcr, the equipment setup was somewhat different since a 13" RCA color television was connected to a RCA (Model 201) Video Cassette Recorder (VCR) employed to deliver the recorded movie, "Godfather II." Figure 10 shows the original timer box was eliminated since VCR subjects would be awake, relaxing in their own bedroom watching the videotape movie. Subjects were required to turn on the Revox tape recorder, turn on the TV monitor and VCR power and press the "play" button on the VCR subjects received the alarm at precisely the same part of the movie. Subjects were told there could be up to five movies extending over that many nights and the experimenter would visit each day to bring the evening movie and synchronize the equipment.

Only the 55 dBA and 70 dBA alarm signal levels were used for the same rationale cited in Experiment Bacn, i.e., the short subject response latencies at 70 dBA. All 20 subjects in Experiment Bvcr selected an hour to watch the video movie that was consistent with their regular nighttime habits. Since more subjects started watching TV between 10:00 p.m. and 11:00 p.m. and the video movie ran 2 1/2 hours, most subjects watched until 1:00 a.m. to 2:00 a.m. Activation of the alarm signal occurred approximately one hour into the second cassette. The movie, "Godfather II" was purchased from Photo Lab Industires. This film satisfied the established criteria, i.e., time duration similar to regular TV programming with commercials added, with a popular movie that appealed to both sexes and was acceptable to both, had varying styles of emotionality, noise, music, violence, passion, etc. The professional recording was chosen for its technical advantages. These criteria were discussed and recommended by the Director of Educational Programming and Research, American Broadcasting System, New York, New York.

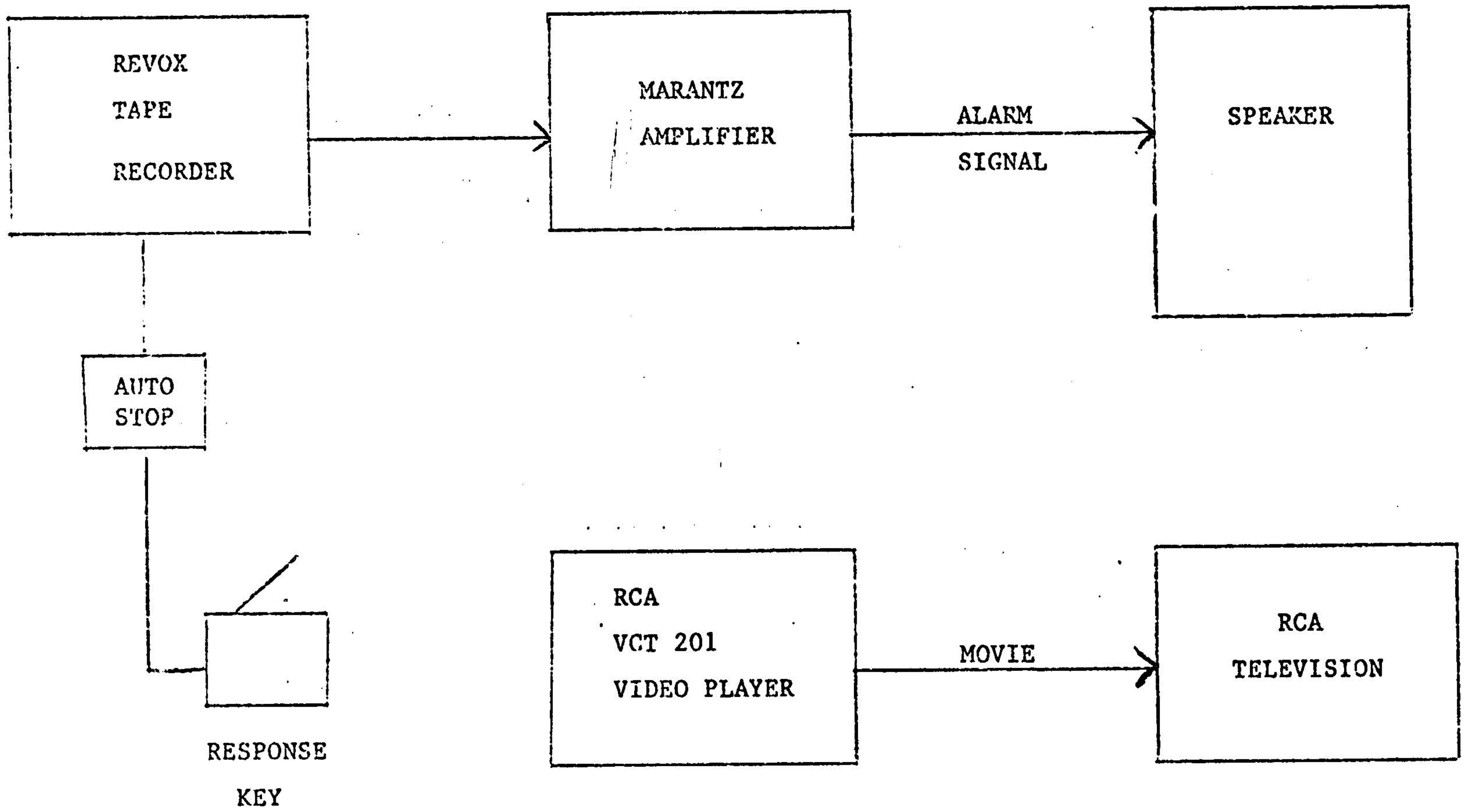

Figure 10

Block Diagram of Equipment Configuration Used in
Experiment Bvcr During Television Viewing

6.1 Results

Data for Experiment Bvcr are presented in Table 12 for the 55 dBA detector signal level and Table 13 for the 70 dBA signal level. Note column A depicts subject response latency to turning off the alarm, column B lists the alarm level and column C designates the TV monitor level range elected during five separate samplings taken at different portions of the movie.

All subjects in Experiment Bvcr responded in 18 seconds or less. At the 55 dBA alarm level, the mean shut-off latency was 9.50 seconds with a range of 04 seconds to 18 seconds. The mean was 5.80 seconds for the 70 dBA alarm level with a range from 03 seconds to 11 seconds. The pooled mean (55 and 70 dBA) was 7.65 seconds for the Experiment Bvcr group compared to 11.55 seconds for Experiment B and 28.94 for Experiment Bacn (Table 8).

T-tests (Table 9), comparing the 55 dBA (13.60 seconds) Experiment B mean vs. the 55 dBA (9.50 seconds) Experiment Bvcr mean, was not significant (p=.060) but differences were highly significant when the 55 dBA (13.60 seconds) Experiment B mean was compared to 70 dBA (5.80 seconds) in Experiment Bvcr (p=.001) and also significant at the p=.017 level when 70 dBA (9.50 seconds was compared to 70 dBA (5.80 seconds). Finally, the pooled (55 and 70 dBA) means comparing Experiment B 11.55 seconds mean to Experiment Bvcr 7.65 seconds mean significantly differed at the p=.007 level of confidence.

T-tests also compared subject response latency means between the air-conditioner noise (Experiment Bacn) and TV movie listening condition (Experiment Bvcr). Significant mean differences occurred (Table 9) between 55 dBA (43.43 seconds) and 55 dBA (9.50) at p=.006; between 55 dBA (43.43 seconds) and 70 dBA (5.80 seconds) at p=.003 and the pooled means (55 and 70 dBA) for Experiment Bacn (28.94) and Experiment Bvcr (7.65) at p=.003. Clearly, the subjects in Experiment Bvcr who watched television and were awakened when the alarm became activated generally had significantly faster shut-off performance responses at each level compared to the other two experiments.

Pearson product moment correlation data for Experiment Bvcr were generally nonsignificant. This was expected since most questionnaire

Table 12

Subject Performance to the 55 dBA Smoke Detector Alarm Sound Level While Viewing VCR Television - Subjects Awake — <u>Experiment Bvcr</u>

Ss#	Sex	Subject Shut-Off Latency (sec)	Detector Alarm Level (dBA)	Television Level Range (dBA)
1	F	11	55	48-52
2	F	10	55	45-50
3	M	04	55	45-47
4	F	04	55	46-50
5	F	11	55	50-55
6	M	05	55	45-48
7	M	18	55	65-72
8	F	10	55	53-55
9	M	14	55	43-47
10	M	08	55	40-45
Mean		9.5	55	
Range		4-18	0	40-72

Table 13

Subject Performance to the 70 dBA Smoke Detector Alarm Sound Level While Viewing VCR Television - Subjects Awake — Experiment Bvcr

Ss#	Sex	Subject Shut-Off Latency (sec)	Detector Alarm Level (dBA)	Television Level Range (dBA)
11	F	03	70	48-53
12	F	04	70	50-55
13	M	08	70	45-49
14	M	10	70	57-62
15	M	04	70	49-52
16	F	05	70	40-45
17	M	05	70	<40
18	F	04	70	55-60
19	M	11	70	55-60
20	F	04	70	< 40
Mean		5.8	70	
Range		3-11	0	40-62

items were related to sleep and this group was awake watching TV. Little information was gleaned from this component that was different from Experiments B and Bacn.

7. SUMMARY AND DISCUSSION

7.1 Purpose of the Research Program

Concern for fire safety in the home has resulted in a notable national effort to enhance safe evacuation in the event of fire. As a result, several million smoke detectors have been purchased in the past several years by safety conscious consumers. Two major factors that will determine the degree of protection offered by household detector units, particularly at night, are the waking effectiveness of household smoke alarm signals and the performance under stress of people awakened by the alarm, i.e., the pattern of stress performance associated with sleep. Hence, this investigation was outlined as a three-year project which purported to answer the following: (1) How effectively do smoke detector alarms awaken people? (2) What is the expected pattern of behavioral performance when people are suddenly awakened from sleep by a detector alarm signal? (3) What alarm improvements can be made to enhance public safety? These questions were translated into three major goals to be explored as a three-year investigation.

Goal I had two distinct phases, Experiment A and Experiments B, Bacn, Bvcr. Experiment A assessed the intensity-frequency characteristics of five smoke detector signals. Overall dBA levels of smoke detector acoustic signals were obtained at 10 and 15 feet from the source in an anechoic chamber and in a reverberant room to simulate the room acoustic continuum found in household installation sites. Smoke alarm signals were analyzed at nine octave bands with central frequencies 63, 125, 250, 1000, 2000, 4000, 8000, 16000 Hz and subsequently refined to 1/3 octave bands. Experiment A was programmed and completed in year 1.

Goal II profiled and quantified sleep-waking behavioral performance of 70 young college-aged subjects relative to alarm signals in three types of listening conditions designated as Experiments B, Bacn, Bvcr. Experiment B (30 Ss) electronically programmed taped detector alarm stimuli in a quiet background. Here the subject responses were the waking-time trial duration latencies from "signal-on" presentation to the subject-initiated "signal-off" (Shut-off) response. This component also included a number of variables, i.e., three alarm sound levels (55, 70, 85 dBA), hours-into-sleep, night-of-week, sex, etc. The three sound levels equated to alarm means calculated earlier from a ten-foot radius (85 dBA), at pillow site, bedroom door open (70 dBA) and at pillow site, bedroom door closed (55 dBA). Sound level was controlled by using a tape recorder smoke detector alarm signal of a current Kobishi-type electromechanical horn, the type used in most household detectors.

One household member served as the experimental respondent and performed two behavior tasks when awakened by the alarm: (1) deactivated the automated apparatus and (2) phoned the Amherst Fire Department. Both responses were recorded and quantified (second units) as S-R latency value. This person also filled out a pre-alarm and a post-alarm questionnaire that contained pertinent behavioral and other supplemental environmental data.

Experiment Bacn (20 Ss) was essentially similar to Experiment B but added about 51 dBA (measured at pillow location) of air-conditioner noise from a loudspeaker generating 63 dBA at window location. The detector alarm signals were 55 dBA (10 Ss) and 70 dBA (10 Ss) measured at pillow location. Accordingly, Experiment Bvcr added a video cassette recording (VCR) as a task to be interrupted by the alarm signal at 55 dBA (10 Ss) and 70 dBA (10 Ss). In this component, the 20 Ss were awake when the alarm signals became electronically activated. Experiment B, Bacn, Bvcr were programmed and completed in year 1.

Experiment C is the field-based component of Goal II to be completed during the second year of the program. Hence, actual smoke detector units will be installed in households to sample households with and without children, apartments vs. homes, time of year. Detectors will be activated by a remote RF signal no sooner than four weeks after installation — the latter serving as the densitization period to the presence of the detector units installed by the experimenter. Two detector units will be installed, the first unit fully operable and a second experimental unit under the RF control of the experimenter capable of remote activation. Subject response requires occupants to turn on a light when awakened and then evacuate all household occupants from the premises to street side of the front door — where an experimenter and a firefighter are strategically located with a stop watch to time the entire waking-evacuation episode.

Goal III, programmed for the third year, will explore the most efficacious acoustic auditory stimuli for different household sleeping conditions and different population types, particularly the handicapped. Further tests will examine different signal temporal patterns for maximum arousal (Experiment D). Other signal variations will consider a speech signal or combination of speech and tone, etc.

7.2 Review of the Literature

An extensive summary of sleep research was outlined in the original grant proposal (May 1978) and later updated in the second year proposal (April 6, 1980). The obvious benefits of a careful review enabled this three-year project to be experimentally designed within a framework of ongoing sleep research with some comparisons to the data elicited in these research projects.

Review outlined sleep stages and the physiological correlates associated with stages 1-4 plus REM. Also, the correlates of stimulus signal, method of presentation, response protocol, age, sex, time of night, hours into sleep, signal significance, cognitive and motivational expectancies, physical and mental conditions, remuneration, experimental site location, intensity magnitude, first night effect, etc. Clearly, the experimental design was partially an outgrowth of the current "state of the art" sleep research and the Nober pilot study outlined in the May 1978 proposal.

7.3 Preparation

Extensive coordination was initiated with the Amherst Fire Department and other segments of the UMass community. Subjects were obtained through a variety of sources and advertisements. Contracts for the protection of human subjects, payments, programming, etc., were explicitly drawn up and discussed on the telephone prior to installation of equipment.

Instrumentation, construction of apparatus, experiment pilot trials, arrangements for use of the anechoic chambers, the reverberant room, additional instrumentation and similar details were all arranged during the early phases of the study. Detail work required multi-faced activities and copious record preparation. Pre- and post-trial questionnaires were printed and pilot tested.

At equipment installation and calibration time, the pre-trial questionnaire was given, a pure tone air-conduction hearing screening test for 10 dBA or better thresholds between 250-8000 Hz inclusive, verbal and written instructions to subjects, stimulus pre-trial practice.

7.4 Experiment A

Experiment A assessed the intensity/frequency spectral characteristics of five popular household smoke alarm units sold in the U.S. Sound level measurements (dBA) were taken in an anechoic chamber and reverberant room at 10 and 15 feet in a 360 degree directional polar axis and analyzed as octave and 1/3 octave bands.

Measures from 10 feet showed a mean of 85 dBA (consistent with manufacturers' claims) with a range from 80-92 dBA. At 15 feet, the mean was 81 dBA with a range from 74-87 dBA. Spectral analysis showed most smoke detector intensity-frequency spectral characteristics were relatively similar with bimodal energy peaks at 4000 Hz (greater) and 2000 Hz (slightly less).

Comparison of spectral characteristics in the anechoic and reverberant rooms revealed somewhat greater intensity variability in the reverberant room. Furthermore, there was a greater angle of incidence variance in peak energy (up to 10 dBA) in the anechoic chamber but only up to 3.5 dBA in the reverberant room. Thus, data from the anechoic chamber — which supposedly represents "peak value" — and data from the reverberant room — which ostensibly designates "average value" — were relatively comparable. Collectively, these data should sample the extremes of possible household acoustic environments.

It is noteworthy that Experiment A revealed considerable variances in the 1/3 octave measurements among the five different smoke detectors and even when measures were taken of different units from the same manufacturer.

7.5 Experiment B

A smoke detector alarm was taped and played back through an electronic timing setup at three sound levels (55, 70, 85 dBA) calibrated to the head/pillow position for 30 normal hearing college-aged subjects in their own households. The three sound levels equated to pillow level bedroom door closed (55 dBA), pillow level bedroom door open (70 dBA), and an unobstructed 10 feet from the sound source (85 dBA). Also, variables of sex, day of week, hour of night, etc., were explored. Pre- and post-trial questionnaires were given to each subject to assess attitudes, habits and other related environmental information. Subject response included "shut-off latency" of the alarm apparatus from when it sounded the alarm to when the subject deactivated the alarm signal. Also measured was latency in seconds to telephone the Amherst Fire Department, where a computer and tape unit timed and recorded subject "phone-call latency."

Experiment B, per se, represented the "quiet" sleep-waking condition with 10 subjects for each of the three sound levels of taped detector alarm signal presentations. Mean shut-off latencies were 13.60, 9.50 and 7.40 seconds for the 55, 70, and 85 dBA levels (Table 7). T-tests revealed significant differences for 55 vs. 85 and 55 vs. 70 and 85 dBA levels (Table 9).

Pearson correlation coefficients for 25 questionnaire items (Table 6) revealed accurate subject self-analysis expectation relative to waking and performance. Hence, subjects who self-rated themselves as "light" or "heavy" sleepers correlated with rapid and slower waking alarm shut-off performance, and correlated positively with subjective and objective coherence data as well as general expectations. Faster shut-off also positively correlated with frequency of regular waking episodes during normal sleep, i.e., the more interrupted the sleep, the faster the waking performance responses. Sex difference was not significant.

7.6 Experiment Bacn

This component used 20 subjects, 10 who received the 55 dBA alarm signal and 10 who received the 70 dBA alarm signal, in the presence of a background air-conditioner noise (*acn*) played from an automatic reversible Teac tape recorder from 8:00 p.m. to 6:00 a.m. nightly. While the air-conditioner noise generated 63 dBA twelve inches from the speaker source of the taped signal, the mean level at pillow position attenuated to 51 dBA. Hence, the signal-to-noise ratios of the two groups differed since the 55 dBA mean S/N was 4.2 dBA (Table 10) and the 70 dBA group mean S/N was 21.0 dBA (Table 11).

Mean shut-off latency was 43.43 seconds for the 55 dBA group (Table 10) and 18.80 seconds for the 70 dBA group (Table 11). The difference was not significant when the three "no response" subjects were excluded from the analyses but highly significant (p=.018) when the three were included using the 240-second coded value. Clearly, the latter three subjects represent 30% of the 55 dBA group — the only instance when subjects failed to awaken or respond in the entire experimental project. *T*-tests also showed significant mean difference when the 55 dBA group in *Experiment B* was compared to the 70 dBA group in *Experiment Bacn*; likewise, both 70 dBA group means differed significantly as did both pooled (55 and 70) means (Table 9).

Correlation analyses revealed similar patterns to *Experiment B* i.e., self-ratings of confidence in smoke alarms in pre- (r=-.47; p=.018) and post- (*4*=-.71; p=.001) trial questionnaires significantly related to shut-off latency and coherency (r=-.60; p=.003).

Analysis of the shut-off response data enabled arranging the 10 subjects of the *Experiment Bacn* 55 dBA group into three divisions, a "fast" response group (3 Ss) with a mean shut-off of 8 seconds, a "medium" response group (4 Ss) with a 70-second mean and the "no response" group (3 Ss). (Note: One of the three responded in 433 seconds but was not included in the analyses.) A stepwise multiple regression was performed with groups assigned as the dependent variable. The variable of frequency of being awakened at night and length of time into sleep when alarm sounded collectively accounted for 89% of the variance. Hence, the "fast" group averaged 190 minutes and the "medium" group averaged 233 minutes into sleep when the alarm sounded.

7.7 Experiment Bvcr

This component used 20 subjects, 10 received the 55 dBA alarm and 10 received the 70 dBA alarm — all while watching a VCR recorded movie "Godfather, II" in the evening prior to bedtime. In this instance, the subjects were awake watching TV — not asleep as in the other experiments. Also, in Experiment Bvcr, subjects controlled their own TV volume setting to simulate normal conditions; hence, specific signal-to-noise ratios were not obtained as their TV loudness varied on an individual basis

At the 55 dBA alarm level, mean shut-off was 9.50 seconds and at 70 dBA it was 5.80 seconds (Table 12) — the difference significant at $p=.040$ (Table 9). Significant mean differences also occurred when the Experiment B 55 dBA mean was compared to Experiment Bvcr 70 dBA ($p=.001$) when both 70 dBA groups were compared ($p=.017$) as well as the pooled (55 dBA and 70 dBA) means of Experiment B and Experiment Bvcr means 55 dBA vs. 55 dBA ($p=.006$), 55 dBA vs. 70 dBA ($p=.003$) and the pooled (55 dBA and 70 dBA) means were compared ($p=.003$). Correlation analysis showed little since the Experiment Bvcr group was awake during the experimental episode.

8. CONCLUSIONS

1. Household smoke detector alarm signals generally provide an 85 dBA sound level within an unobstructed 10 foot distance.

2. The detector alarm signals have acoustic spectral characteristics that vary among manufacturer models. Most units have bimodal energy peaks with the primary peak around 4000 Hz and the secondary peak around 2000 Hz.

3. Within a ten-foot prescribed radius, the detector alarm signals had means that varied between 3-10 dBA in a 360 degree axis. Tests were conducted in an anechoic chamber and a reverberant room to sample the acoustic characteristic extremes for household detector installation sites. Results revealed minor sound level variations resulting from absorption and reflection.

4. The three experimental detector alarm levels, i.e., 85 dBA (NFPA requirement at 10 feet), 70 dBA (sound level at pillow location, bedroom door open), 55 dBA (sound level at pillow, bedroom door closed)

were all sufficient to awaken, young normal-hearing college-aged adults from sleep at varying hours of the night, and days of the week, when the alarm was presented in quiet.

5. Waking latency means (second units) differed significantly when comparing 55 dBA vs. 70 dBA and 55 dBA vs. 85 dBA but not significantly between the 70 dBA and 85 dBA levels. While the differences were statistically significant in absolute time, the values never exceeded a full minute.

6. Variables of sex, time of night, day of week did not yield significantly different mean latency shut-off responses or for the task requirement to telephone the local Amherst Fires Department after the detector alarm sounded.

7. A taped 63 dBA noise from a 6000 BTU window air conditioner set at high-fan, compressor cooling mode significantly increased the waking latency at the 55 dBA and 70 dBA alarm levels (85 dBA, not tested) compared to the quiet and VCR-TV experimental conditions. With the air-conditioner noise present, the 55 dBA alarm group had 20% (2 subjects) who failed to awaken from the alarm and 10% (one subject) who exceeded four minutes. In this 55 dBA condition, the S/N ratio was about 4 dB.

8. Subjects who were not asleep but watching a video-recorded TV movie when the detector alarm sounded, responded to the alarm within the shortest latency shut-off time at both the 55 dBA and 70 dBA alarm levels.

9. With appropriate motivation and sensitization normal hearing young subjects can be aroused from sleep and expected to perform coherent tasks when the detector alarm level is 55 dBA in a quiet setting. At 70 dBA subjects in quiet and with the background air conditioner noise were awakened but in the noise condition the S/N ratio was about 21 dB.

10. Questionnaire data generally showed that subjects accurately projected whether they were "light" or "heavy" sleepers and would be awakened rapidly from the detector alarm signal. Subjects who played radio or TV sets in their bedrooms prior to sleep, generally awakened faster than subjects who did not use these facilities on a regular basis.

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APPENDIX A

SMOKE DETECTOR RESEARCH PROJECT

Subject Hearing Screening

DATE: ______________________

TO: Leah Watkins

FROM: Dr. Charles Johnson

Please set up a hearing screening appointment with the subject listed below and conduct the test between th se dates ______________ and ______________. Use the IAC chamber, if subject can come in, otherwise, go to the subject's home or apartment within the dates listed.

Subject's Name: ______________________________

Address: ______________________________

Telephone: ____________________

= =

HEARING SCREENING TEST RESULTS

Date Test Administered: ____________________ Place: ____________________

Screening Level: 10 dB in all frequencies used ____ (Check). If different indicate level used and in what frequencies.

	250	500	1000	2000	4000	8000
Right						
Left						

(NOTE: Return this form when completed to Dr. Peirce.)

SMOKE DETECTOR RESEARCH

Pre-Trial Questionnaire
Experiment B

Subject Code:______________

1. Respondent:__________________ (first name) Household Status:__________________
   Sex:____________ Age:______________

2. Location of residence: Street______________________ Apartment?______
   City______________________ House?______

3. Occupant (first name) Sex Bedroom# Age dBA Occupant (first name) Sex Bedroom# Age dBA

   a.____________________________ e.____________________________

   b.____________________________ f.____________________________

   c.____________________________ g.____________________________

   d.____________________________ h.____________________________

4. Household pets? Type and number:______________________________

5. Type of location of residence: City__________ City suburb __________
   Town__________ Rural____________

6. Approximate age of house:__________

7. Construction: Wood frame__________ Brick__________ Other____________
   Style:____________________

8 Ceiling height of bedrooms:____________ Exception/s________________

9. Number of floor levels including basement:__________

10. Overall dwelling size:

	square feet	ceiling height	cubic feet
Basement level:			
First floor:			
Second floor:			
Third floor:			
TOTAL:			

11. Does anyone in the household have any known hearing impairment? __No __Yes

If yes, whom? ____________________ Bedroom location? ____________________

12. Rate daytime neighborhood noise level (circle one number).

1	2	3	4	5
Quiet		Moderate		Noisy

Comments: (What kind of noise?)

13. Rate nighttime neighborhood noise level (circle one number).

1	2	3	4	5
Quiet		Moderate		Noisy

Comments: (What kind of noise?)

14. When the windows are closed, are you ever awakened at night or kept up by noise at your present residence?

_______No; _______Yes. If yes, about how often? ____every night/week;

____4-6 nights/week; ____1-3 nights/week; ____a few nights/month; ____rarely.

Comments: (What kind of noise awakens you?)

15. When the windows are open, are you ever awakened at night or kept up by noise at your present residence?

_______No; _______Yes. If yes, about how often? ____every night/week;

____4-6 nights/week; ____1-3 nights/week; ____a few nights/month; ____rarely.

Comments: (What kind of noise awakens you?)

16. Rate yourself and others as sleepers, on "workdays" (or school days) and "nonworkdays" (weekends, holidays, vacation, etc.) using the following scale:

1 - very light 2 - moderately light 3 - average

4 - moderately heavy 5 - very heavy

(first name)	WORKDAY	NONWORKDAY
a. ______ (respondent)		
b. ______		
c. ______		
d. ______		
e. ______		
f. ______		
g. ______		
h. ______		

17. Do you have a routine "workday" (or schoolday) sleeping pattern?

_____No; _____Yes. If yes, what is the pattern?

If no, explain.

18. Do you have a different "nonworkday" (weekend, holiday, vacation, etc.) sleeping pattern?

_____No; _____Yes. If yes, what is the pattern?

If no, explain.

19. Estimate the number of sleep hours per night. (Circle the appropriate number.)

Workday	3/or less	4	5	6	7/or more
Nonworkday	3/or less	4	5	6	7/or more

20. Estimate the number of times your sleep is interrupted per night for personal reasons (toilet, insomnia, allergy, etc.). (Circle the appropriate number.)

Workday	3/or less	4	5	6	7/or more
Nonworkday	3/or less	4	5	6	7/or more

21. Estimate the number of times your sleep is interrupted per night by household forces (baby, children, pets, etc.). (Circle the appropriate number.)

Workday	3/or less	4	5	6	7/or more
Nonworkday	3/or less	4	5	6	7 or more

22. Do you take alcohol and/or drugs before going to sleep? _____No; _____Yes.

If yes, which one? _____alcohol; _____drugs. About how often?

_____every night/week; _____4-6 nights/week; _____1-3 nights/week;

_____a few nights/month; _____rarely.

Does this affect your sleep pattern? _____No; _____Yes. If yes, comment:

23. Do you run an air conditioner or large fan in your bedroom during warm weather:

_____No; _____Yes. If yes, how often do you leave it on all night:

_____every night/week; _____4-6 nights/week; _____1-3 nights/week;

_____a few nights/month; _____rarely.

Does this affect your sleep pattern? _____No; _____Yes. If yes, comment:

24. Do you have a radio, TV, or any other noise producing unit in your bedroom? ____No; ____Yes. If yes, which one and how often do you play the unit when you go to bed?

__________________(unit); _____every night/week; _____4-6 nights/week;

_____1-3 nights/week; _____a few nights/month; _____rarely.

25. How often do you fall asleep with the unit playing:

_____every night/week; _____4-6 nights/week; _____1-3 nights/week;

_____a few nights/month; _____rarely.

26. Does the unit get turned off? _____No (plays all night); _____Yes.

If yes, when_______________________, and by whom?_________________________

27. Rate your confidence that you can be safely awakened by a smoke detector alert device once sounded in the event of a true fire. (Circle one.)

1	2	3	4	5
No Confidence	Slight	Moderate	Very Confident	Complete Confidence

28. In the space below draw a rough floor plan of the house or apartment. Indicate who sleeps in which bedroom. Mark location of telephone (T) and location of equipment installed -- tape recorder (TR), smoke detector (SD), and location of switch to turn off equipment (S).

Re: Placement of equipment: Indicate intensity levels re: _____dBA in:

Bedroom 1 ____dBA; 2 ____dBA; 3 ____dBA; 4 ____dBA; 5 ____dBA; 6 ____dBA.

29. Results of pure tone AC screening test for Respondent re: 10dB.

	250	500	1000	2000	4000	8000
Right						
Left						

Date:______________________ Audiometer______________________

Room:______________________ dBA level______________________

30. Is there some external noise (such as a garbage truck) which occurs on a regular basis that you are aware of? ____ No; ____ Yes. If yes, identify the noise and the day and time it happens.

APPENDIX C

SMOKE DETECTOR RESEARCH

Post-Trial Questionnaire
Experiment B

Subject Code:________________

1. Name each member of the household who was home the night the alarm sounded and encircle which ones were awakened by the sound of alarm (as opposed to activity following alarm).

a.________________ (Respondent) c.________________ e.________________ g.________________

b.________________ d.________________ f.________________ h.________________

2. When the alarm sounded, were you or any household members already awake (not asleep) at that moment?

_____No; _____Yes. If yes, whom?____________________

3. When the alarm sounded, list household members in order of arousal from sleep, starting from first awakened to last.

1st______________ 3rd______________ 5th______________ 7th______________

2nd______________ 4th______________ 6th______________ 8th______________

4. Including yourself, rate how lucid or coherent each awakened person appeared immediately after alarm sounded. (Scale is a 5 point range with 1 the least coherent and 5 the most coherent. Check one for each person.)

	1 incoherent	2 partially coherent	3 moderately coherent	4 very coherent	5 totally coherent
a.________ (Respondent)					
b.________					
c.________					
d.________					
e.________					
f.________					
g.________					
h.________					

Respondent: Elaborate on <u>your</u> coherentness:

5. Did you in fact turn off the alarm? _____Yes; _____No. If no, who did, and why?

6. Did you in fact telephone the fire department? _____Yes; _____No. If no, who did and why?

7. On the night the alarm sounded, about what time did you fall asleep? __________ About what time do you normally fall asleep? ______________

8. About how long were you asleep when the alarm awakened you? ___________ hours.

9. On the night that the alarm sounded, how tired were you when you went to sleep? (5 point scale)

   1. ___________much less tired than usual
   2. ___________less tired than usual
   3. ___________about the same as usual
   4. ___________more tired than usual
   5. ___________extremely more tired than usual

Any relevant information about other people in the household?

10. Was an air conditioner, large fan, radio, T.V., or any other noise producing unit on in any bedroom when the alarm sounded? _____No; _____Yes. If yes,

which bedroom?______________________ What kind of unit?______________________

11. On the night the alarm sounded were there any special circumstances before going to sleep which might have changed your sleeping behavior or that of any other household member? Please identify person and explain.

12. Describe events that occurred after the alarm sounded.

13. Were there any special or unusual occurrences when the alarm sounded? (Such as animals waking up and making noise, etc.)
_____No; _____Yes. Describe.

14. Were any neighbors awakened by the alarm when it sounded? _____No; _____Yes; _____Don't know. Did any complain? _____No; _____Yes.

15. Was your sleeping pattern altered in any way by the knowledge that you were likely to be awakened by an alarm signal or by the presence of the equipment? (Check one for each night of involvement.)

	1 not at all	2 slightly	3 moderately	4 considerably	5 consistently
First night					
Second "					
Third "					
Fourth "					
Fifth "					
Sixth "					
Seventh "					
Alarm night					

16. From this personal experience rate your confidence in being safely awakened by a smoke detector alert device once activated in the event of a true fire. (Circle one.)

1	2	3	4	5
no confidence	slight	moderate	very confident	completely confident

APPENDIX D

SMOKE DETECTOR RESEARCH PROJECT

R E C E I P T

On ____________________, I received a smoke detector alarm unit as part
(Date)

of the remuneration for our household's participation in the Smoke Detector Research Project directed by Dr. E. Harris Nober, Principal Investigator, Department of Communication Disorders, University of Massachusetts. I received and read the Privacy Act Statement concerning the request for information solicited on the two questionnaires being used as part of the Smoke Detector Research Project.

____
(Signature)

SMOKE DETECTOR RESEARCH PROJECT

R E C E I P T

On ____________________, I received a smoke detector alarm unit as part
(Date)

of the remuneration for our household's participation in the Smoke Detector Research Project directed by Dr. E. Harris Nober, Principal Investigator, Department of Communication Disorders, University of Massachusetts. I received and read the Privacy Act Statement concerning the request for information solicited on the two questionnaires being used as part of the Smoke Detector Research Project.

____
(Signature)

Town of

APPENDIX E

AMHERST Massachusetts

FIRE DEPARTMENT
JOHN T. DOHERTY. CHIEF

April 7,1980

Professor Harris E Nober
Arnold House
University of Massachusetts
Amherst, Mass. 01003

Dear Dr. Nober:

Thank you for reviewing with me your progress and preliminary data on your investigation into the "Waking Effectiveness of Household Smoke Detection Devices." I am pleased to know that our dispatchers, and especially the services of Principal Dispatcher Robert Chisholm, have been of help in the project.

I am very much interested in your proposed step of allowing a much longer period in which your subjects can be expected to become less sensitized to the presence of the test detector before the actual triggering of the device. The greater control allowed by remote radio activation of the device accompanied by actual on-site observation of the household reactions should prove most valuable in firming up the data.

Please be assured of our continuing co-operation (without cost) in this project. This letter will serve to confirm my verbal offer to provide a department car to transport, or assist, your investigator in the early morning hours when he might possibly be mistaken for a prowler or intruder.

I continue to believe that investigations such as yours are vital to clinically establishing the effectiveness of these devices. Many of us in the fire service have vigorously promoted smoke detectors (we are aware of 13,500 devices in place in Amherst) and hunger for objective and disinterested evaluations on which we can rely.

Very truly yours,

John T Doherty

John T Doherty
Fire Chief

APPENDIX F

(FOLLOW THESE INSTRUCTIONS EXACTLY WHEN YOU PHONE THE FIRE DEPARTMENT)

1. DIAL 253-3431

   (THE PERSON ANSWERING WILL SAY: "AMHERST FIRE DEPARTMENT")

2. SAY CLEARLY: "PROJECT DETECTOR"

3. ANSWER ANYTHING ELSE ASKED OF YOU BY THE FIRE DISPATCHER.

****

NOTE: If you need to get in contact with the research people, call the following:
Dr. Charles Johnson--545-2089 (before 5PM) or 665-3094 (after 5PM)
Dr. E. Harris Nober--545-2089 (before 5PM) or 253-5616 (after 5PM)
Dr. Henry Peirce -- 545-2089 (before 5PM) or 253-7005 (after 5PM)

Ask each question only once.
If you do not understand the answer, continue on to the next question.
Ask questions only as written.

Dispatcher: "Amherst Fire Department."

Subject: "Project Detector."

Dispatcher: "Project Detector; I understand."

"What telephone number are you calling from?"

"Is the alarm shut off?"

"Who shut it off?"

"Were you asleep?"

"Who woke you up?"

"What day of the week is this?"

"Do you know what time it is?"

"Is everyone awake, or is someone still sleeping?"

Dispatchers are to remove the telephone tape at this point and save it.

****

INSTRUCTIONS GIVEN TO CALLERS IN THESE TESTS:

(To be followed EXACTLY!)

1. Dial 253-3431 (Person answering will say "Amherst Fire Department.")
2. Say CLEARLY: "Project Detector."
3. Answer anything else asked of you by the fire dispatcher.

NBS-114A (REV. 2-80)

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5. AUTHOR(S)

E.H. Nober, H. Peirce, A. Well, C.C. Johnson and C. Clifton

6. PERFORMING ORGANIZATION (If joint or other than NBS, see instructions)

University of Massachusetts
Amherst, MA 01003

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NBS Grant DA0001

8. Type of Report & Period Covered

9. SPONSORING ORGANIZATION NAME AND COMPLETE ADDRESS (Street, City, State, ZIP)

National Bureau of Standards
Department of Commerce
Washington, DC 20234

10. SUPPLEMENTARY NOTES

☐ Document describes a computer program; SF-185, FIPS Software Summary, is attached.

11. ABSTRACT (A 200-word or less factual summary of most significant information. If document includes a significant bibliography or literature survey, mention it here)

Normal-hearing, young adults were subjected to home smoke detector alarm signals of 85, 70, and 55 dBA while asleep in their own bedrooms under quiet background conditions. In addition, other adults received 70 and 55 dBA alarm signals masked by window air conditioner background noise. Each person, upon awakening from the alarm signal, was instructed to shut off the alarm and telephone the local fire department. The 85, 70, and 55 dBA alarm levels were all sufficient to awaken the subjects at varying hours of the night and days of the week, under quiet background conditions. While there were statistically significant differences in waking times between 55 dBA and the other two alarm levels, the total times never exceeded 115 seconds for the combined alarm shutoff and the fire department telephone call at any alarm level. With background noise, waking times for the 70 and 55 dBA alarm levels increased (85 dBA not tested). At 70 dBA, the total time for the alarm shut-off and the fire department telephone call ranged from 36 to 119 seconds. At 55 dBA, two persons failed to awaken and one person awakened after the four-minute test termination criteria. For the remaining seven persons, the total time for the combined alarm shutoff and the fire department telephone call ranged from 45 to 137 seconds.

12. KEY WORDS (Six to twelve entries; alphabetical order; capitalize only proper names; and separate key words by semicolons)

Adults; alarm responses; auditory perception; decibal levels; fire departments; frequency distribution; noise (sound); sleep; smoke detectors; wakefulness

13. AVAILABILITY

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